UNIVERSITY OF SOUTHAMPTON
FACULTY OF ENGINEERING AND THE ENVIRONMENT
INSTITUTE OF SOUND AND VIBRATION RESEARCH

# PREDICTING THE VIBRATION DISCOMFORT OF STANDING PASSENGERS IN TRANSPORT

by

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ABSTRACT

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It has previously been assumed that the vibration discomfort of standing people can be estimated using the same procedures developed from for seated people. In this thesis, the discomfort of standing people exposed to vibration was investigated to improve understanding of the mechanisms responsible for discomfort and construct a model that may be used to predict the discomfort of standing railway passengers.

The first of five experiments using the method of magnitude estimation and 6-s periods of vibration investigated how the discomfort of standing subjects exposed to fore-and-aft, lateral, and vertical sinusoidal vibration depends on the frequency of vibration. From the judgements of 12 subjects at each of the 16 preferred one-third octave centre frequencies from 0.5 to 16 Hz, frequency weightings were constructed for each direction. For vertical vibration, the weighting was similar to that recommended in standards, but the weightings for fore-and-aft and lateral vibration differed from that previously assumed. Horizontal vibration caused loss of balance at frequencies less than about 3 Hz, and it caused discomfort in the legs at higher frequencies. Vertical vibration caused discomfort in the upper body. To adjust the frequency weightings according to differences in sensitivity between directions, the second experiment with 12 subjects compared the discomfort caused by 4-Hz sinusoidal vibration in the fore-and-aft, lateral, the vertical directions. It was found that sensitivity was greater for fore-and-aft vibration than lateral vibration at frequencies less than 4 Hz and weightings were determined to assist the evaluation vibration in all three directions. The third experiment investigated the extent to which postural supports used by standing train passengers (vertical bar, shoulder support, and back support) affect discomfort caused by fore-and-aft and lateral vibration in the range 0.5 to 16 Hz. Supports that created a new path for the transmission of vibration to the upper-body increased discomfort over the range 4 to 16 Hz.

The fourth experiment investigated how the root-mean-square method, the basic evaluation method in current standards but known to underestimate the discomfort caused by motions containing occasional peaks, could be modified for the evaluation of non-sinusoidal vibration. Using 1-Hz and 8-Hz random vibrations with a range of crest factors it was found that the discomfort of standing subjects was better predicted with an exponent around 3, rather than an exponent of 2 implicit in r.m.s. averaging. The final experiment determined a method for predicting the discomfort of tri-axial vibration. The cube root of the sum of the cubes of the discomfort caused by the single-axis components gave good estimates of the total discomfort for both 1-Hz and 4-Hz tri-axial vibration. Since it was found in the first experiment that the discomfort was generally proportional to the acceleration at the power 0.7. these results suggest that the root-sum-of-squares of the accelerations gives good estimates of the total discomfort for tri-axial vibration .

The results of all experiments were combined in an empirical model for predicting the discomfort of standing people exposed to 6-s periods of vibration. It is concluded that there are two distinctly different mechanisms responsible for vibration discomfort when standing: postural instability and body vibration. Postural instability is dominant with horizontal vibration at frequencies less than about 3 Hz, whereas body vibration is dominant with vertical vibration and with horizontal vibration at frequencies greater than about 3 Hz. The discomfort of standing people is similar to the discomfort of seated people for vertical vibration, but fundamentally different with horizontal vibration due to postural instability at low frequencies and vibration attenuation in the legs at higher frequencies.

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# DECLARATION OF AUTHORSHIP

I, OLIVIER THUONG

declare that the thesis entitled

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and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
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- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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Signed: ..........................................................................................

Date:..............................................................................................

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# Nomenclature

| | |
|---|---|
| $\psi$ | Subjective magnitude (discomfort) |
| $\varphi$ | Objective magnitude (in general, r.m.s. acceleration) |
| $k$ | 'Constant' in Stevens power law |
| $n$ | 'Exponent' in Stevens power law |
| $f$ | Frequency |
| $\omega$ | Angular frequency ($\omega = 2\pi f$) |
| $K_3(i,j)$ | Relative sensitivity between directions $i$ and $j$ ($K_3(i,j) = \frac{K_i}{K_j}$) |
| $\epsilon$ | Magnitude estimation bias (Chapters 5 and 9) |
| r.m.s. | Root-mean-square: r.m.s.= $\left[\frac{1}{T}\int_0^T a(t)^2 dt\right]^{1/2}$ |
| r.m.q. | Root-mean-quad: r.m.q.= $\left[\frac{1}{T}\int_0^T a(t)^4 dt\right]^{1/4}$ |
| VDV | Vibration dose value: VDV= $\left[\int_0^T a(t)^4 dt\right]^{1/4}$ |
| MTVV | Maximum transient vibration value: MTVV=max $\left\{\left[\frac{1}{\tau}\int_{t_0}^{t_0+\tau} a_w(t)^2 dt\right]^{1/2}\right\}_{t_0=0..T-\tau}$ |
| $\lambda$ | Exponent used for the evaluation of motions containing transients (Chapter 7) |
| $\tau$ | Integration time for the calculation of running r.m.s. (Chapter 7) |
| $f_{\lambda,\tau}$ | $f_{\lambda,\tau}(a) = \max\left\{\left[\frac{1}{\tau}\int_{t_0}^{t_0+\tau} \lvert a_w(t)\rvert^\lambda dt\right]^{1/\lambda}\right\}_{t_0=0..T-\tau}$ |
| $rm_\lambda$ | $rm_\lambda = \left[\frac{1}{T}\int_0^T \lvert a(t)\rvert^\lambda dt\right]^{1/\lambda}$ |
| $VD_\lambda$ | $VD_\lambda = \left[\int_0^T \lvert a(t)\rvert^\lambda dt\right]^{1/\lambda}$ |
| $\alpha$ | Exponent used for the summation of axes (Chapter 8) |
| $A$ | Masking coefficient (Chapter 8) |
| $r$ | Repeatability coefficient (Chapter 9) |
| $s$ | Imaginary frequency: $s = i\omega = 2\pi i f$ |

# Chapter 1

# Introduction

As the transport industry is challenged by the need for increased passenger capacity, travelling in a standing position is becoming more common. To maintain a competitive advantage, transport operators and manufacturers will wish to ensure that this evolution does not happen to the detriment of the comfort of passengers.

One of the main components of ride comfort in public transport is vibration. The discomfort experienced by standing passengers when vibration is transmitted from the structure of the vehicle to their bodies depends highly on the characteristics of the vibration. Knowledge of the relation between the characteristics of the vibration and discomfort is essential for optimizing the efforts aiming at reducing the contribution of vibration to discomfort. This relation cannot be predicted with purely physical models, and must be based on a subjective model, because discomfort is a subjective quantity that cannot be measured directly.

Many researchers have investigated the discomfort of seated people exposed to vibration, but the understanding of the discomfort of standing passengers is limited. Knowledge of the discomfort of seated people has been used to construct methods for predicting the discomfort of standing people that are included in International and British standards (ISO 2631-1, 1997; BS 6841, 1987).

This thesis sets out to investigate the relations between the discomfort of standing people exposed to vibration, and the characteristics of the vibration. Understanding these relations and the mechanisms of discomfort allows the construction of a model predicting the vibration discomfort of standing people, which can be compared with the method advocated in standards.

In the model, the prediction of discomfort was broken into several steps, which are summarized in Figure 1.1. The knowledge necessary to construct each step of the model was obtained in separate experiments. Five experiments were conducted in the laboratory of

Table 1.1: Summary of the five experiments reported in Chapters 4 to 8 of this thesis.

| **Chapter** | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|
| **Variable investigated** | Frequency | Direction | Postural supports | Waveform (random and transients) | Multi-axial vibration |
| **Waveform** | Sinusoidal | Sinusoidal | Sinusoidal | Octave-band random with selected peakiness | Octave-band random |
| **Frequencies** | 1 Hz to 16 Hz (preferred octave frequencies) | 4 Hz | 1 Hz to 16 Hz (preferred third-octave frequencies) | 1Hz, 8 Hz | 1Hz, 4 Hz |
| **Posture** | Standing | Standing | Standing, using body supports | Standing | Standing |
| **Subjective method** | Magnitude estimation | Magnitude estimation | Magnitude estimation | Magnitude estimation | Magnitude estimation |
| **Duration of stimuli** | 6 s | 6 s | 6 s | 6 s | 6 s |
| **Direction of reference / dir. of test** | x/x,<br>y/y,<br>z/z | x/y, y/x,<br>x/z, z/x,<br>y/z, z/y | x/x<br>y/y | x/x,<br>y/y,<br>z/z | x+y+z / x+y+z |
| **No. of subjects** | 16 | 12 | 12 | 20 | 16 |
| **Visual field** | Closed field | Eyes closed | Open field | Eyes closed | Eyes closed |
| **Magnitudes ($m.s^{-2}$ r.m.s.)** | 0.04-0.66 to 0.22-4.17 | 0.15-0.29 to 0.69-1.37 | 0.05-0.4 to 0.32-2.54 | 0.2-0.8 to 0.32-1.27 | 0.09-0.19 to 0.38-0.75 |

the Human Factors Research Unit at the Institute of Sound and Vibration Research (University of Southampton). The five experiments are reported in Chapters 4 to 8, and a summary of the objectives and designs of all five experiments is included in Table 1.1.

Following this introduction, Chapter 2 includes a review of the literature related to the vibration discomfort of standing and seated people. In Chapter 3, the methods used in this thesis are presented (in particular, the equipment, testing conditions, methods, and analysis tools). In Chapters 4 to 8, five experiments are reported, as summarized in Figure 1.1 and Table 1.1, investigating the effect of frequency, direction, postural support, waveform, and the discomfort caused by multi-axis vibration. Chapter 9 contains a discussion of the methods and results of all experiments, for the construction of a model explaining the mechanisms of the discomfort of standing people, and Chapter 10 presents a predicting

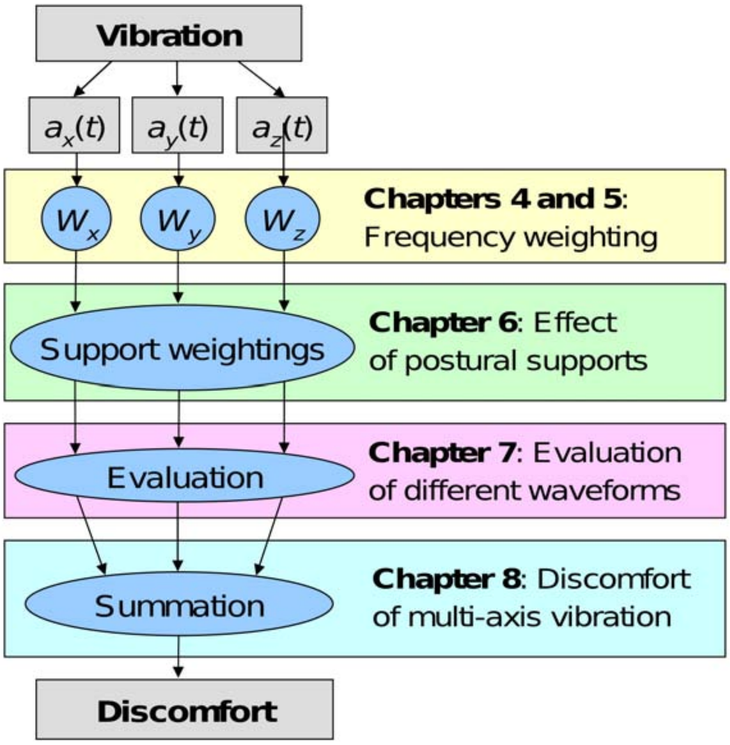


Figure 1.1: Structure of the thesis, based on the construction of a model of the vibration discomfort of standing people.

model constructed from the knowledge gathered in the experiments. Chapter 11 concludes this thesis.

The appendix shows the instructions provided to subjects in all experiments, the script for some functions used for the analysis of data, and the data for some of the figures presented in this thesis.

# Chapter 2

# Literature review

## 2.1 Introduction

This chapter presents the foundations on which the research presented in this thesis was built. Since the 1930s, awareness of the importance of the discomfort caused by vibration in vehicles and buildings has grown, and many studies have been conducted to investigate different aspects of vibration discomfort.

In Section 2.2, conceptual and methodological considerations are presented, discussing the nature of discomfort and possible methods for investigating, in particular, vibration discomfort. In Section 2.3, the effect of factors such as the characteristics of vibration (frequency, magnitude, duration, waveform, direction) and the posture and characteristics of subjects on vibration dicomfort is discussed. Although some results were obtained with standing people, most studies were conducted with seated subjects. They are also reported in this review as their results may apply to standing people. Section 2.4 presents an overview of possible causes of vibration discomfort; in Section 2.5, methods for predicting the vibration discomfort are discussed, in particular the methods recommended in International and British standards.

## 2.2 Investigation of vibration discomfort

### 2.2.1 The nature of discomfort

#### 2.2.1.1 Definitions of comfort

The concept of 'comfort' is difficult to define and measure. Branton (1972) suggested that comfort could only be defined in terms of its absence, because only discomfort could actually be felt: a state of comfort is thence reached when the individual does not feel any discomfort. Indeed, although some investigators have tried to assess positive comfort, most attempts to assess comfort have actually assessed discomfort.

Comfort can be defined as an optimal state in which the individual does not take any further step to avoid discomfort (Shackel *et al.*, 1969), or has no awareness of his environment (Branton, 1969), or can give all his attention to any activity he wants to carry out (Branton, 1972). From the behavioural point of view, individuals are active comfort seekers, and their response can be interpreted as attempts to reduce discomfort. Changes of posture or clothing are examples of comfort responses that tend to reach an optimum state. This principle can also be used in the laboratory, when asking subjects to compare two stimuli. Instead of asking subjects which stimulus is more comfortable or uncomfortable, it is possible to ask which one they would prefer to have reduced if they had to be exposed to both stimuli again. It is assumed that the subjects will give answers that will reduce their discomfort, choosing the most uncomfortable stimulus to be reduced; this procedure avoids having to define the word ‘comfort’ to the subjects.

#### 2.2.1.2 The subjectivity of comfort

Comfort is, by nature, subjective. So, its measurable nature is questionable; and if it is assumed to be measurable, it is practically difficult to measure. A subjective quantity cannot, by definition, be measured directly or observed by an external person. Indeed, the subjects solely have access to their level of comfort. It is necessary that they assess their discomfort themselves and report it to the investigator. In these two steps, psychological and methodological biases may occur.

First of all, judgments made by subjects about their levels of comfort or discomfort result in intra-subject and inter-subject variability. Richards *et al.* (1978) suggested that the comfort of a passenger depended on the environment (motion inputs, other sensory factors, seat, and space factors) but also on the characteristics of the passengers. Potentially relevant parameters include physiological factors, but also psychological factors (attitudes, beliefs, expectations, fears, moods, and anxiety), and situational factors (flight experience, or more generally, travel experience on the studied transport mode, socioeconomics status, demographic characteristics). In addition, estimating discomfort can be a difficult task and the same subject may provide different answers when exposed twice to the same motion stimulus (inter-subject variability).

For example, people having a good image of air transport and like flying tend to find aircraft environment more comfortable than a person who does not like flying (Richards *et al.*, 1978). The reason for this is assumed to be that when a passenger has an opinion about a transport mode, the selectivity of his perception will allow him to notice elements that match this opinion, and filter out things that do not.

Psychological parameters can therefore interfere with the rating of transport environment. But they must also be taken into account in the laboratory environment. For example, many researchers have asked subjects or passengers to rate comfort of stimuli on an "adverb-adjective scale" (e.g. Chaney, 1965). This means that the subjects are presented a stimulus and are asked to choose from a scale a category that describes the stimulus. Typical category labels are "slightly uncomfortable", "very uncomfortable", "acceptable", "not acceptable", "fairly unpleasant", etc. These scales may be difficult for the subjects to use in a consistent way, because the rating depends on the frame of reference of the subjects, including past experience, expectations about riding comfort, transport mode taken as a reference, but also the range of stimuli presented (see Section 2.2.5.2).

#### 2.2.1.3 The importance of passenger comfort

The importance of comfort for transport resides in the link existing between satisfaction and comfort. Satisfaction is liable to invoke a willingness to use the same transport mode again (Oborne, 1978a), which is the main objective of the efforts made by operators and manufacturers to improve comfort. To investigate this relation, Richards *et al.* (1978) studied the influence of different factors on the choice of a transport mode based on questionnaires filled in by airline passengers. A first sample of passengers rated safety and reliability as the most important factors of choice, followed by time savings, convenience, comfort and cost. A second sample of passengers rated time savings and times of arrival and departure as the most important factors, followed by convenience and ride comfort. Although these results are probably prone to a large variability (as shown by the differences between the results from the two samples), it appears that comfort, if not the main factor, influences the choice of transport mode. This was confirmed in the study by the correlation between the comfort rating and the "willingness to use the same transport mode again".

### 2.2.2 Methods for studying passenger discomfort

The science dealing with the use of the knowledge of the interactions between human beings and their environment for the design of systems is called environmental ergonomics. In this definition, the 'environment' includes all inputs received by the body in a given situation, in particular light and visual input, sound, motion, heat, contact and shapes.

#### 2.2.2.1 Methods of environmental ergonomics

Parsons (2000) distinguished four different types of method used in environmental ergonomics: subjective, objective, behavioural, and modelling methods.

- **Subjective methods** require subjects or users to report their perceptions of their responses to an environment. Simple scales or more elaborated questionnaires can be used. These methods have the advantage of being practically easy to use (relatively little instrumentation), and are the most appropriate way to assess psychological subjective responses such as comfort. They have the disadvantage of being fussy to design, because of many possible methodological biases due to psychological factors.
- **Objective methods** obtain direct measurements of the response of the body to an environment, for example, the acceleration of body members, body temperature, performance at a task, hearing abilities, or heart rate. Psychological biases are avoided with these methods, but they have disadvantages. In particular, measuring instruments can sometimes modify the quantity they are measuring. Furthermore, these methods cannot directly be used to assess subjective responses such as discomfort. Some attempts have been made to relate subjective comfort to objective quantities such as heart rate, but this still needs to be investigated.
- **Behavioural methods** are based on the observation of the behaviour of subjects or passengers (for example, changes of posture, particular postures, blinking). Conclusions on the response to an environment can be derived from these observations, using models of the relations between response and behaviour. An advantage of these methods is that they do not interfere with the quantity they are measuring. However, an interpretation model is needed, and it is sometimes difficult to be certain about the cause of a given behaviour.
- **Modelling methods** are based on models of environmental responses. They have the advantage brought by models: they are convenient to use, consistent, quick, and can be used in both design and evaluation. But models predicting human response are often too simple to take account of all parameters influencing responses.

Often, a combination of subjective, objective, behavioural and modelling methods is used.

#### 2.2.2.2 Research environments

The methods presented in Section 2.2.2.1 can be applied in different environments. Oborne (1978c) distinguished three environments where research on comfort may be carried out: the field environment with real passengers, the field environment with subjects, and the laboratory.

- The field environment with passengers is the most naturalistic frame, and is ideal for studying the transport mode in a ‘systems’ approach. Questionnaire studies (subjective methods) are the most appropriate way and the most used method for collecting data in this environment, although behavioural observations are also possible. Questionnaire studies enable the researcher to identify which parameters are important for passengers exposed to the real environment. An example of such studies is reported by Richards *et al.* (1978), who carried out a survey based on questionnaires filled in by airline passengers, about comfort and satisfaction. The objective of the study was to determine which factors were perceived as most important for comfort and which factors were the most correlated with the satisfaction of real airline passengers. Questionnaire studies are difficult to design and to analyze, because it must be made sure that the questions are unambiguous, and that the aim of the study has been fully understood (Oborne and Clarke, 1973).

- The field environment with subjects provides to the experimenter more control of the variables than studies using real passengers, and enables the experimenter to use the same subjects to compare different vehicles or environments. For example, the method of paired comparison was used by Manenica and Corlett (1973) and Aspinall (1960). They compared, respectively, a number of transport modes (bus, hovercraft, ferry), and several different cars, by having subjects use two different vehicles sequentially, and compare them on some specific aspects. After each pair of vehicles had been compared by every subject, global comparisons within the whole set of vehicles could be made using statistical tools. Rating scales have also been used with subjects in field environments, in which they probably are easier to process than with real passengers, because subjects are likely to be more controllable than passengers. Another method used in this environment is behavioural observation. Assuming that passengers or subjects are active comfort seekers, observation of their behaviour in a real vehicle environment can provide useful information about their comfort. For example, Branton and Grayson (1967) observed the behaviour of subjects on a train using different types of seat, and derived conclusions about the comfort of the seats from observations of changes of posture, general posture (slouched or straight), etc.

- The laboratory environment allows much more control over the variables by the experimenter. Studies that start from a naturalistic global point of view (using a field environment) may naturally lead to more molecular studies on particular aspects of comfort. A laboratory environment is the most appropriate way to investigate systematically the effect of characteristics of vibration. It is possible to ask subjects to adjust stimuli to match specific sensations, to ask subjects to rate the discomfort caused by stimuli, to measure psycho-physiological responses (skin resistance, heart rate, etc.), or to observe performance, while controlling the stimuli in a very precise and repeatable way. Laboratory experiments offer a very wide range of possibilities for the investigation of the effects of vibration on comfort.

### 2.2.3 Vibration discomfort

#### 2.2.3.1 Stevens' power law

Finding a relation between a physical input and the perceived magnitude of the physical input has been the object of many studies. Stevens (1956) postulated that for any given simple stimulus (i.e., not a composite stimulus), the sensation magnitude, $\psi$, can be related to the stimulus physical magnitude, $\varphi$, by the following power law:

$$\psi = k\,\varphi^n \tag{2.1}$$

where the exponent (also called rate of growth of sensation), $n$, and the constant, $k$, are assumed to be constant for a given stimulus (for example, vibration in a given direction and at a given frequency).

Since its publication, the validity of this law has been verified for a whole range of stimuli, including sound and vibration, brightness, warmth, length, heaviness and duration.

An alternative version of this law includes the perception threshold $\varphi_0$, which is the lowest magnitude of stimulus that can be perceived by a subject:

$$\psi = k\,(\varphi - \varphi_0)^n \tag{2.2}$$

Stevens' power law is widely used for modelling vibration discomfort.

#### 2.2.3.2 Semantic scales

An early conception (as stated by Reiher and Meister, 1931) was that the sensitivity to vibration only depended on acceleration. Reiher and Meister (1931) conducted a comprehensive study showing that the sensitivity to vibratory acceleration actually depended on frequency, and established equivalent comfort contours, using an adverb-adjective scale: subjects were presented vibration stimuli at various frequencies and magnitudes, and asked to chose a category for each of them. The scale included 'not perceptible', 'clearly perceptible' and 'very unpleasant'. This work was the first comprehensive work on the subject, although some more basic studies had been published before.

Following the work by Reiher and Meister (1931), 'Adverb-adjective' scales have been extensively used to try and provide absolute assessment of comfort. This means that subjects were exposed to motions and were asked to classify them into categories defined by expressions such as "very unpleasant", "slightly uncomfortable", etc. The validity of such scales has been investigated by Dempsey *et al.* (1977) and Suzuki (1998a). Dempsey *et al.* (1977) showed that the results of studies using this type of scale depended on the scales and terms used. Suzuki (1998a) showed that the results depended on the range (the lowest and the highest presented stimuli) and the frequency (the number of times each stimulus was presented) of the stimuli. Basically, subjects tend to use the same range of ratings, regardless of the absolute magnitudes of the stimuli. So, a given vibration stimulus will obtain higher discomfort ratings if it is one of the greatest magnitudes presented than if it is one of the smallest magnitudes presented.

Another disadvantage of such scales is the difficulty encountered when trying to compare experiments using different terms. Oborne (1978c) gathered results from seven different studies using semantic scales to try to relate the magnitude and frequency of vibration with the sensation it causes. All studies were anterior to 1965. The studies used terms as different as “mildly annoying”, “definitely perceptible”, “undeniable sensation”, “well noticeable”, “pleasing”, “comfortable”. Comparing these results requires the interpretation of the terms, which is fussy. Oborne (1978c) stated that “little agreement exists between various investigators as to which levels differentiate ‘comfortable’ from ‘uncomfortable’ ”.

Because of the difficulties encountered with semantic scales, most later studies were designed to construct contours of equivalent sensations without having recourse to semantic scales. These contours show the equivalence between vibration at different frequency, but without necessarily associating a label to them.

#### 2.2.3.3 Different methods to produce comfort contours

An equivalent comfort contour is a curve which shows, for a number of frequencies, the magnitude of (generally, sinusoidal) vibration that causes a given magnitude of discomfort. An equivalent comfort contour is defined for a given direction of vibration, and is associated with a particular subjective magnitude, which may or may not be associated with a semantic label.

Most methods for constructing equivalent sensation contours require to present pairs of vibration to subjects. Pairs consist in a reference motion followed by a test motion. Two large groups of methods can be used to determine comfort contours: ‘magnitude production’ methods and ‘magnitude estimation’ methods (Stevens, 1975). ‘Magnitude production’ means that subjects respond by adjusting the magnitude of the test vibration, whereas with magnitude estimation, subjects respond by providing a value representing the discomfort of the test motion.

For both magnitude production and magnitude estimation methods, three different types of reference can be used:

- Same-frequency reference: the test signal has the same frequency as the reference signal, but a different magnitude. The subject is then asked to adjust the test signal until its magnitude is felt as a given multiple or fraction of the reference (half, twice, ten percent, etc.). Assuming the validity of Stevens' power law (Stevens, 1957), equivalent sensation contours can be derived.

- 'Moving reference': the subjects are first exposed to a reference vibration at frequency $f_1$ followed by a test vibration at frequency $f_2$, which they have to adjust or rate in comparison with the reference at frequency $f_1$. Then, subjects are exposed to a reference motion at frequency $f_2$, and a test motion at frequency $f_3$, and so on. Comfort contours are derived by mathematical induction (for example, Oborne and Boarer, 1982a, with magnitude production).
- Fixed reference: The reference vibration is held constant over a whole experiment (for example, Morioka and Griffin, 2006a, with magnitude estimation).

Magnitude production with the reference and test motions at different frequencies (both fixed and moving) yield, directly, comfort contours. Magnitude estimation methods are less direct, and require the data to be processed, in general by performing linear regressions based on Stevens' power law (Section 2.2.3.1).

#### 2.2.3.4 The method of constant stimuli

Another group of method was developed, based on the method of the 'constant stimuli': subjects are presented vibration in pairs, and asked to compare the two motions in the pair, generally indicating which of the test or the reference is more uncomfortable. Depending on the answer, the experimenter modifies the magnitude of one of the motions in order to approach the equivalent magnitude, where the test and the reference cause equivalent discomfort. The method of constant stimuli may be considered as a magnitude estimation method, because subjects are asked to provide an answer describing the vibration.

The method of constant stimuli was used, for example, by Griffin and Whitham (1980) to investigate the discomfort caused by impulsive vibration motions.

A summary of the methods presented in this section is presented in Table 2.1

Table 2.1: Summary of possible methods used to construct equivalent sensation contours.

| **Method** | **Type of reference** | **Response** |
|---|---|---|
| Magnitude production without reference | Semantic label | Adustment of test stimulus |
| Magnitude production with reference | Reference vibration | Adjustment of test stimulus |
| Estimation without reference | None | Numerical value |
| Estimation with reference | Reference vibration | Numerical value |
| Constant stimuli | Reference vibration | Binary comparison |

### 2.2.4 Developments in investigation of vibration discomfort

#### 2.2.4.1 Frequency weightings

From the concept of equivalent sensation contours, the concept of frequency weightings was derived. A frequency weighting is a curve representing the relative sensitivity to vibration at different frequencies, and can be practically used to weight a vibration motion, which is usually the first step in the evaluation process. Usually, frequency weightings are derived from equivalent sensation contours by simply inverting the contours and normalizing them with an arbitrary constant.

#### 2.2.4.2 Other applications

The focus of researchers working on the vibration discomfort was primarily the effect of frequency, leading to the construction of equivalent sensation contours. As the interest on the topic grew, researchers investigated other aspects of vibration discomfort, such as the effect of duration, waveform or magnitude. Most methods presented in Section 2.2.3.3 can be used for other applications than equivalent comfort contour, as they are methods for converting subjects' sensations into measurable quantities.

### 2.2.5 Discussion of subjective methods

The different subjective methods presented in the previous sections have specific shortcomings or limitations that the experimenter must be aware of.

#### 2.2.5.1 The effect of duration

When magnitude production is used, subjects are generally presented a continuous vibration which they adjust until the discomfort reaches a particular level. This means that the experimenter has no control over the duration of exposure, which may vary, depending on the time needed by the subject to make the adjustment. As noted by Fairley and Griffin (1988), it is known that the discomfort caused by vibration increases with the duration of exposure; therefore, the discomfort perceived by the subjects depends on the duration of the vibration, which is not controlled by the experimenter. This is likely to add some variability and possible a bias towards underestimating vibration (Fairley and Griffin, 1988).

#### 2.2.5.2 The effect of range

As shown by Suzuki (1998a), the discomfort estimates reported by subjects depend on the range of stimuli presented. This means that the particular choice of magnitudes, which may be different at different frequencies, may affect the shape of equivalent sensation contours, for example. Suzuki (1998a) used a magnitude estimation method without reference motions. When reference motions are used, this effect is expected to be minimized.

#### 2.2.5.3 Order effects

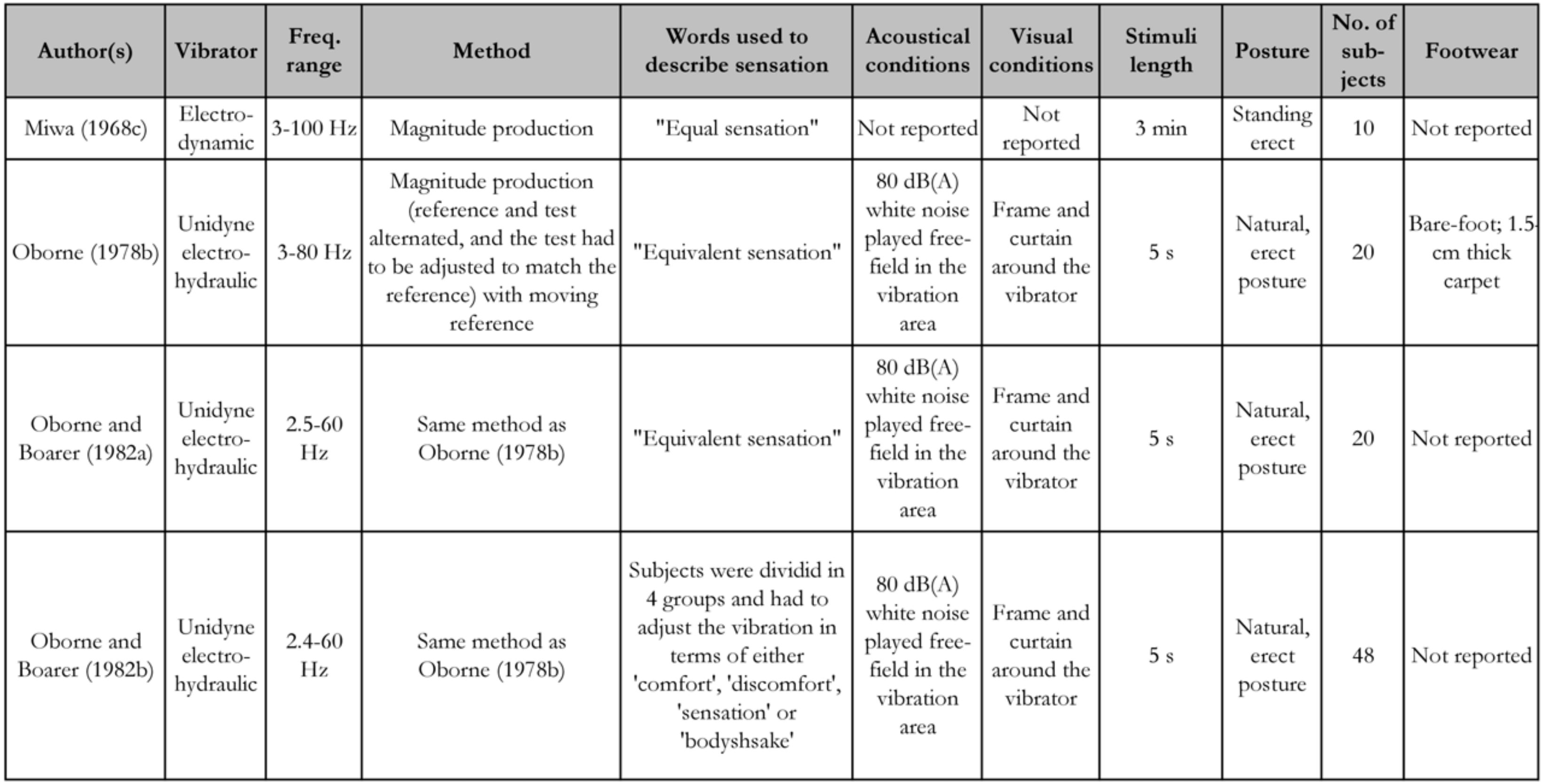
With all methods where motions are presented in pairs, order effects can be observed. When an order effect occurs, the subjective judgement of the second motion of the pair is biased compared to the first motion, and, in particular, vibration that cause equivalent discomfort will not be perceived as equivalent. For example, Fairley and Griffin (1988) used a magnitude adjustment method and found that subjects tend to underadjust the magnitude of the test stimulus, presented after the reference. Griffin and Whitham (1980) used a constant stimuli method, and observed a bias towards judging the second motion more uncomfortable. This bias was reduced by repeating the sequence ‘reference-test’ twice.

Table 2.2: Summary of the studies in which equivalent sensation contours for standing people were constructed (part 1/2).

| Author(s) | Vibrator | Freq. range | Method | Words used to describe sensation | Acoustical conditions | Visual conditions | Stimuli length | Posture | No. of sub-jects | Footwear |
|---|---|---|---|---|---|---|---|---|---|---|
| Chaney (1965) | Electro-hydraulic | 1-27 Hz | Magnitude production - semantic scale | Subjective levels to match: "perceptible", "mildly annoying", "extremely annoying", 'alarming" (defined in the instructions) | Not reported | Eyes open (eyes closed permitted) | Continuous | Not reported | 5 | Boot tops over the ankles, feet and shoes. Leather shoes |
| Ashley (1970) | Electro-hydraulic | 0.7-20 Hz | Magnitude production (with broadband random reference) | Subjects had to chose "which [motion] is more unpleasant" | Earmuffs worn for reducing noise | Not reported | Continuous | Standing naturally (not rigidly ), not bending knees | 27? | Not reported |
| Jones and Saunders (1972) | Derritron VP85 Electro-magnetic | 4-80 Hz | Magnitude production (reference and test alternated, and the test had to be adjusted to match the reference) | Reference and test had to be adjusted to be "equal in sensation on a comfort basis" | Ambient noise was reduced to 51 dbA | Not reported | 8 s | Standing without bending the knees | 10 | "normal clothing" |
| Oborne and Clarke (1974) | Unidyne electro-hydraulic | 3-80 Hz | Magnitude estimation using a scale (subjects rated stimuli on a line scaled from 0 to 10) | Vibration was rated in terms of a numeric scale ranging from 0 (smooth) to 10 (rough) | White noise presented through headphones | Frame and curtain around the vibrator | Not reported | Not reported | 12 | Not reported |
| Miwa (1967a) | Electro-dynamic | 0.5-300 Hz | Magnitude production | "Equal sensation" | Not reported | Not reported | 3s (10 Hz and more) or 6s (less than 10 Hz) | Standing erect | 10 | Not reported |

*(Continued on next page)*

Table 2.3: Summary of the studies in which equivalent sensation contours for standing people were constructed (part 2/2).



| Author(s) | Vibrator | Freq. range | Method | Words used to describe sensation | Acoustical conditions | Visual conditions | Stimuli length | Posture | No. of sub-jects | Footwear |
|---|---|---|---|---|---|---|---|---|---|---|
| Miwa (1968c) | Electro-dynamic | 3-100 Hz | Magnitude production | "Equal sensation" | Not reported | Not reported | 3 min | Standing erect | 10 | Not reported |
| Oborne (1978b) | Unidyne electro-hydraulic | 3-80 Hz | Magnitude production (reference and test alternated, and the test had to be adjusted to match the reference) with moving reference | "Equivalent sensation" | 80 dB(A) white noise played free-field in the vibration area | Frame and curtain around the vibrator | 5 s | Natural, erect posture | 20 | Bare-foot; 1.5-cm thick carpet |
| Oborne and Boarer (1982a) | Unidyne electro-hydraulic | 2.5-60 Hz | Same method as Oborne (1978b) | "Equivalent sensation" | 80 dB(A) white noise played free-field in the vibration area | Frame and curtain around the vibrator | 5 s | Natural, erect posture | 20 | Not reported |
| Oborne and Boarer (1982b) | Unidyne electro-hydraulic | 2.4-60 Hz | Same method as Oborne (1978b) | Subjects were dividid in 4 groups and had to adjust the vibration in terms of either 'comfort', 'discomfort', 'sensation' or 'bodyshsake' | 80 dB(A) white noise played free-field in the vibration area | Frame and curtain around the vibrator | 5 s | Natural, erect posture | 48 | Not reported |

In general, the second motion in a pair is perceived as more uncomfortable than the first motion.

#### 2.2.5.4 Difficulty of comparing different motions

Most methods for investigating vibration discomfort require subjects to compare vibration stimuli. Comparing the discomfort caused by two similar motions is fairly easy, but when the motions cause sensations of very different nature, the task becomes more difficult. This may be due to the motions in a pair having very different frequencies, different directions, or different waveforms.

As a consequence, the variability in the judgements increases with the 'difference' between the two motions to be compared. In particular, the dispersion of estimates increases with the frequency difference between the two motions in a pair. This lead to the creation of 'moving reference' methods (Section 2.2.3.3), in which only vibrations with similar frequencies are compared.

## 2.3 Factors influencing vibration discomfort

### 2.3.1 The effect of the frequency on the discomfort of standing people

#### 2.3.1.1 Vertical vibration

The earliest comprehensive study of the frequency-dependence of the discomfort of standing persons exposed to vertical vibration was reported by Reiher and Meister (1931). Equivalent comfort contours have subsequently been produced by Chaney (1965), Miwa (1967a, 1968c), Ashley (1970), Jones and Saunders (1972), Oborne and Clarke (1974), Oborne (1978b), and Oborne and Boarer (1982a, 1982b). A summary of the methods used in these studies is provided in Tables 2.2 and 2.3.

Comfort contours obtained by these researchers are shown in Figure 2.1. They were obtained at different magnitude levels, so for allowing comparison of their shapes they were normalized so that their minimum value is 1.0.

Despite the variety of methods used, the comfort contours obtained in different studies are consistent. However, two different general shapes of contours can be observed. Most contours have a minimum value at a single frequency, which is in the range 5 to 8 Hz, but a small number of contours reached their minimum value (indicating a maximum of sensitivity) over the whole range 5 to 15 Hz. The two shapes of contours are shown in Figures 2.2 and 2.3.

The comfort contours of the second type were obtained in the following studies:

- The contour for 'perceptible' vibration obtained by Chaney (1965) (contours for 'mildly annoying', 'extremely annoying' and 'alarming' were of the 'type 1')
- The contour for one of the 'profiles' identified by Oborne (1978b). In this study, equivalent sensation contours were constructed for a sample of subjects, and three profiles of subjects, with different shapes of comfort contours, were identified.
- The contour obtained by Oborne and Boarer (1982b) corresponding to equivalent 'comfort' (as opposed to 'discomfort', 'sensation' or 'body shake').
- All equivalent sensation contours obtained by Ashley (1970).

Analysis of Tables 2.2 and 2.3 does not show any obvious common characteristic between those contours, so no reason was identified as the cause for the differences in the shapes of the contours.

#### 2.3.1.2 Horizontal vibration

Few studies have produced comfort contours for standing people exposed horizontal vibration. Contours obtained by Miwa (1967b, 1968c) are shown in Figure 2.4; these contours were obtained with the same methods as the vertical contours, which are shown in Tables 2.2 and 2.3. The shape of the contours suggest that standing people are sensitive to acceleration in the frequency range 0.5 to 4 Hz (the contours are similar to horizontal lines) and to velocity in the range 4 to 100 Hz (the contours are similar to lines of constant velocity).

#### 2.3.1.3 Very low frequency vibration

Yonekawa and Miwa (1972) investigated the discomfort caused by very low frequency horizontal and vertical oscillation (0.05 Hz to 2.0 Hz). The resulting contours are shown in Figure 2.5. In this range of frequencies, the sensitivity to acceleration was approximately constant in both directions.

### 2.3.2 The effect of the magnitude of vibration

#### 2.3.2.1 Magnitude-dependence of equivalent sensation contours

It has long been recognized that the sensitivity of the human body to vibration acceleration is not the same at all frequencies. However, the frequency-dependence itself seems to depend on the magnitude of the vibration. This phenomenon is referred to as 'magnitude dependence'. The evaluation methods advocated in all current standards (ISO 2631,

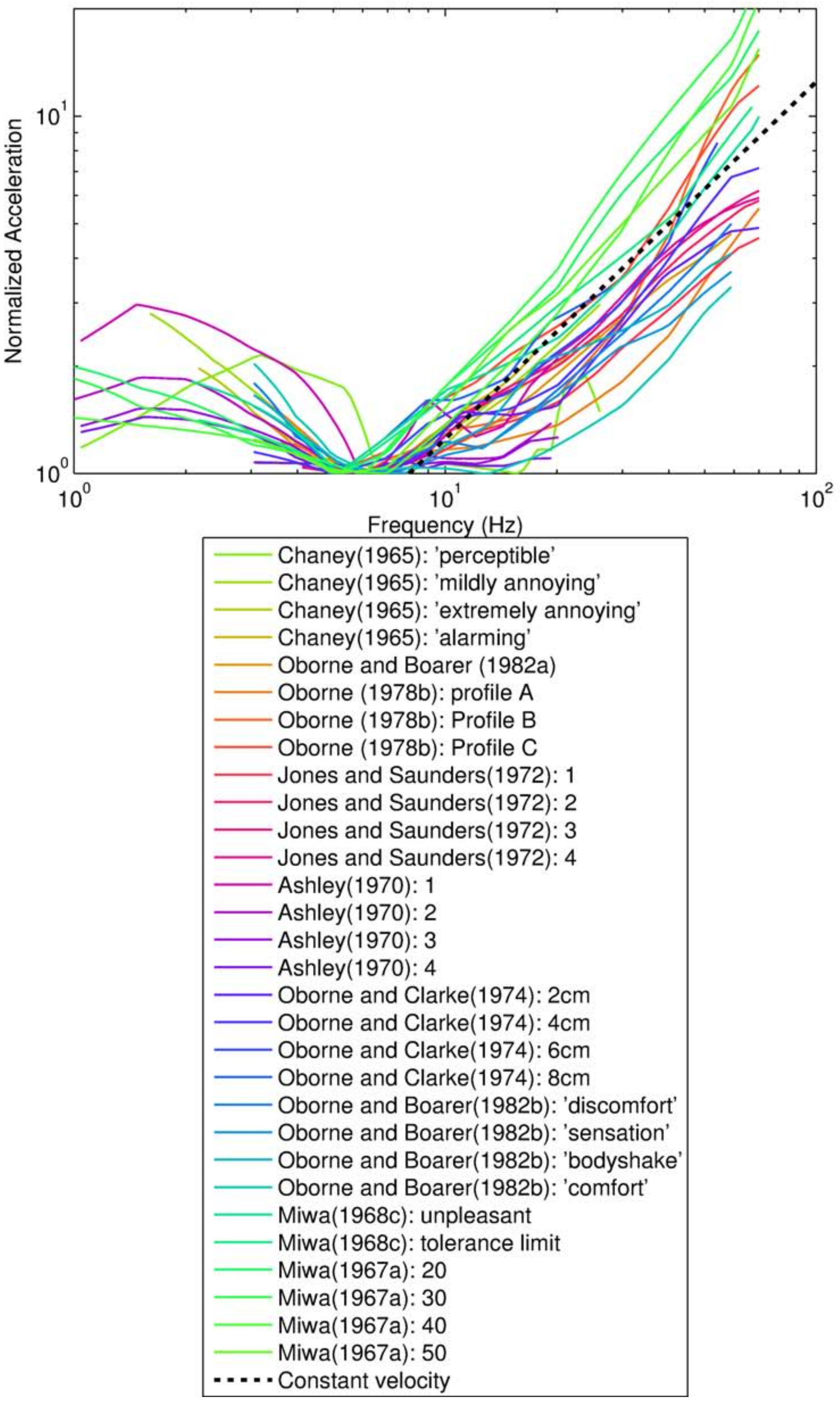


Figure 2.1: Normalized equivalent sensation contours for standing people exposed to vertical vibration, obtained in previous studies.

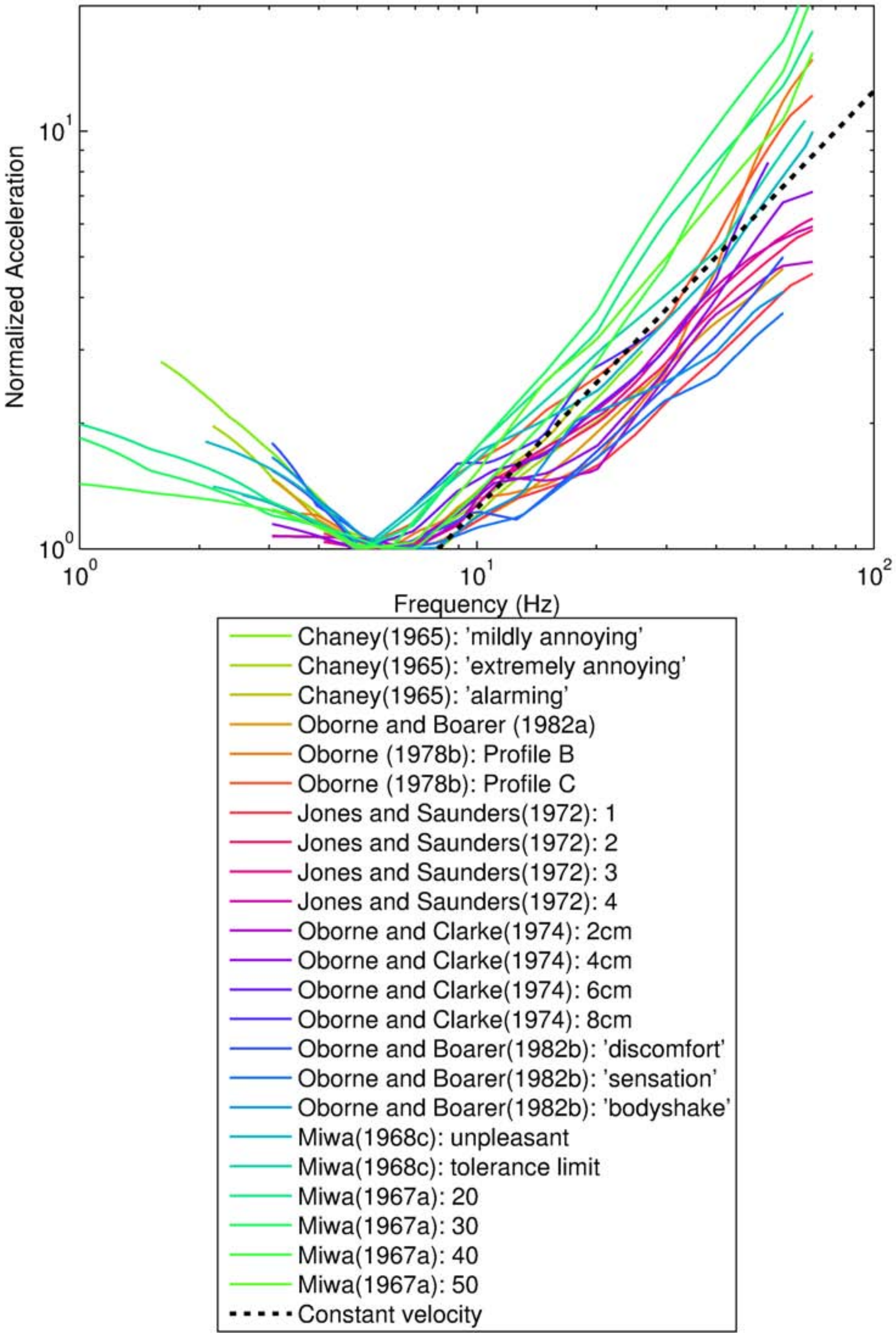


Figure 2.2: Normalized equivalent sensation contours for standing people exposed to vertical vibration: first type (single frequency of maximum sensitivity).

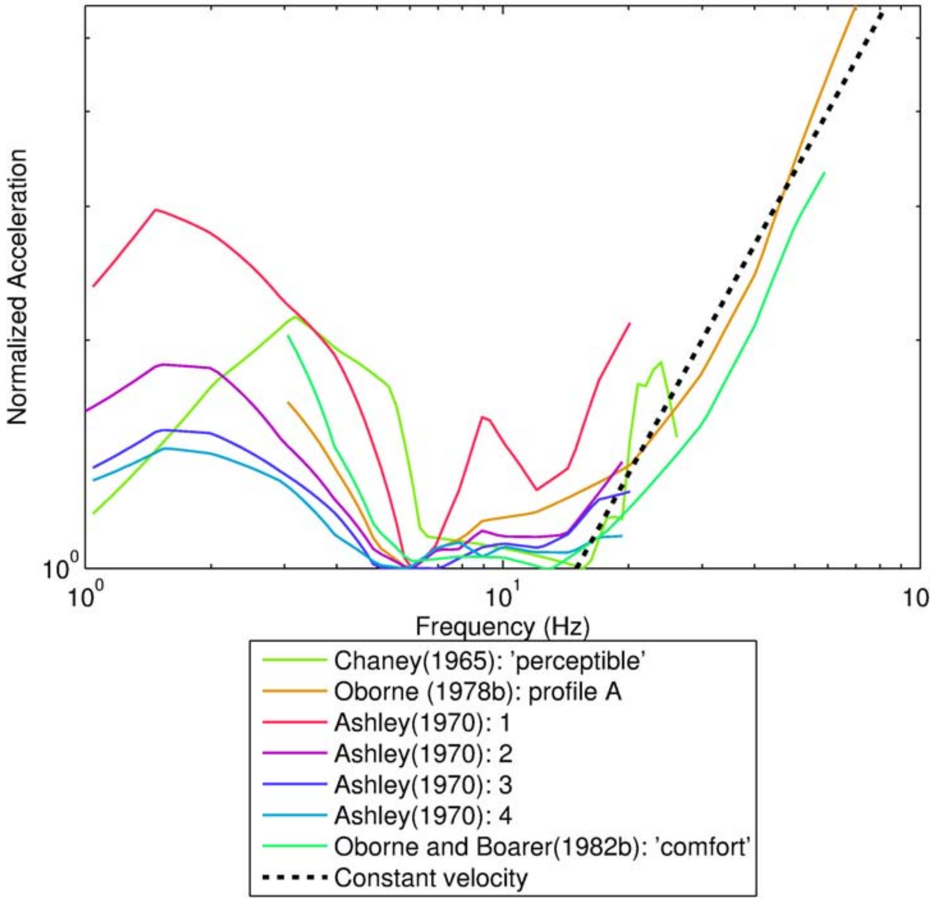


Figure 2.3: Normalized equivalent sensation contours for standing people exposed to vertical vibration: second type (maximum of sensitivity over the range 5 to 15 Hz).

1997, BS 6841, 1987) use the same frequency weighting at all magnitudes, ignoring any magnitude-dependence.

### 2.3.2.2 Studies showing no magnitude dependence

Miwa (1967a) produced equivalent comfort contours at different magnitudes and concluded that the contours constructed at different magnitudes were "found to parallel each other at regular amplitude intervals", suggesting that there was no magnitude-dependence. Similarly, other researchers such as Ashley (1970) and Jones and Saunders (1972) obtained comfort contours at different magnitudes and reported that the contours seemed to be parallel. Yonekawa and Miwa (1972) stated: "it is supposed from our previous experiences that the level dependency is negligible, if the level is not taken to ultimate values near threshold of perception or of pain", suggesting that no magnitude-dependence had been shown by previous research in the middle of the magnitude range.

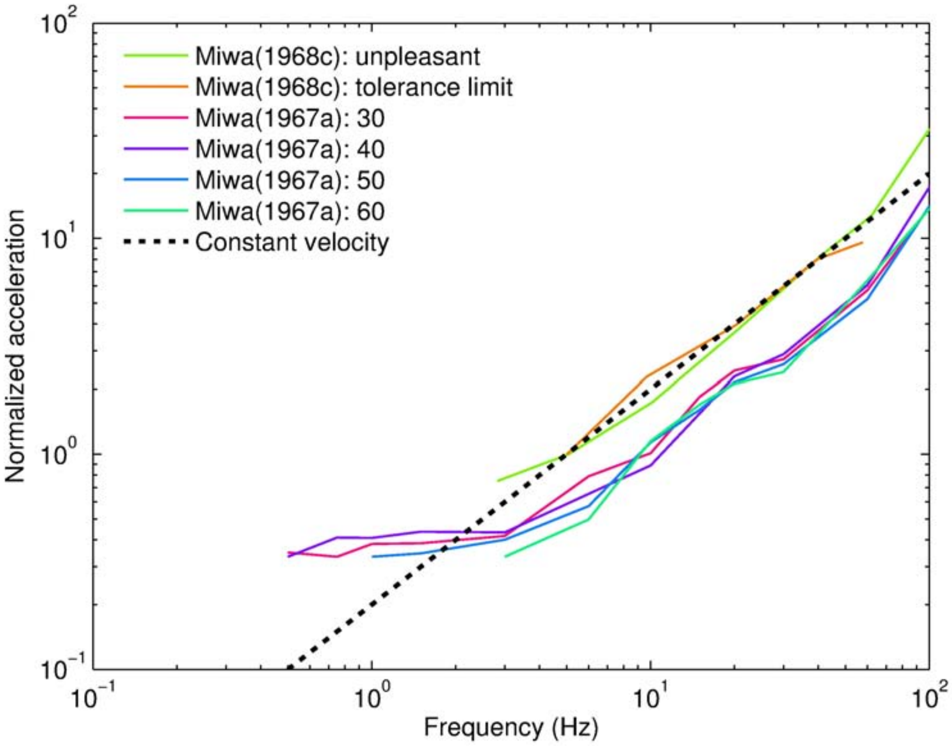


Figure 2.4: Normalized equivalent sensation contours for horizontal vibration.

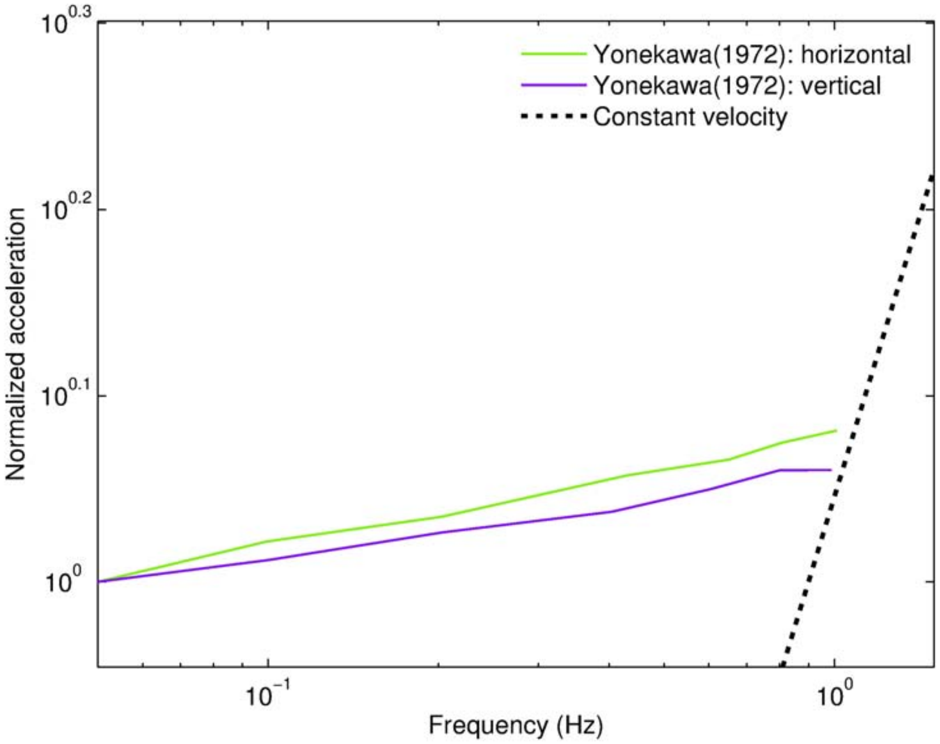


Figure 2.5: Normalized equivalent sensation contours for low-frequency vibration.

#### 2.3.2.3 Evidence of a magnitude dependence

Reiher and Meister (1931), who carried the first comprehensive study of vibration discomfort of standing people, drew lines separating different zones (such as 'perception zone', 'annoyance zone', 'danger zone') and found that the perception thresholds were described by constant velocity lines, whereas the 'damage threshold' in the vertical direction was described by a line of constant acceleration. The boundaries between zones (which are equivalent sensation contours) were described by lines of constant $d\,f^k$, where $d$ is the displacement and $f$ the frequency, and $k$ a constant exponent (for example, $k = 1$ represents lines of constant velocity and $k = 2$, constant acceleration). It was found that the exponent $k$ increased gradually with the magnitude. This means that the shape of the contours changed with the magnitude of vibration.

Oborne and Clarke (1974) also noted, after constructing equivalent sensation contours for seated people, that the contours "change[d] in shape at different levels of subjective intensity", and that such an alteration of contours by magnitude had also been observed by Ashley (1970), Shoenberger and Harris (1971) and Jones and Saunders (1972).

The first comprehensive studies specifically designed to investigate the effect of magnitude were conducted by Morioka and Griffin (2006a, 2006b), who investigated the magnitude-dependence of equivalent comfort contours of seated subjects exposed to whole body vibration (Morioka and griffin, 2006b) and hand-transmitted vibration (Morioka and Griffin, 2006a). The range of magnitudes included magnitudes close to the perception threshold. With whole-body vibration, the authors found that the shape of the equivalent comfort contours at magnitudes close to the perception threshold were different from the shapes of contours obtained at higher magnitudes. Some of the equivalent comfort contours obtained by Morioka and Griffin (2006b) are shown in Figure 2.6, where the magnitude-dependence is clearly noticeable. The magnitude-dependence of equivalent sensation contours was related with the frequency-dependence of the rate of growth of sensation, $n$ (the exponent in Stevens' power law, Section 2.2.3.1). It is likely that similar effects would be observed with standing people.

#### 2.3.2.4 Causes of the magnitude dependence

For hand-transmitted vibration, the magnitude-dependence has been partly explained by the existence of several perception channels, sensitive to different frequencies and having different perception thresholds. For whole-body vibration, the perception of vibration is more complex, involving receptors of very different kinds in the whole body. Whitham and Griffin (1978) and Landström and Lundström (1986) showed that that the parts of the body where discomfort arises depend on the magnitude of vibration. A non-linearity in the biodynamic response, and the existence of several perception channels could explain the magnitude-dependence of comfort.

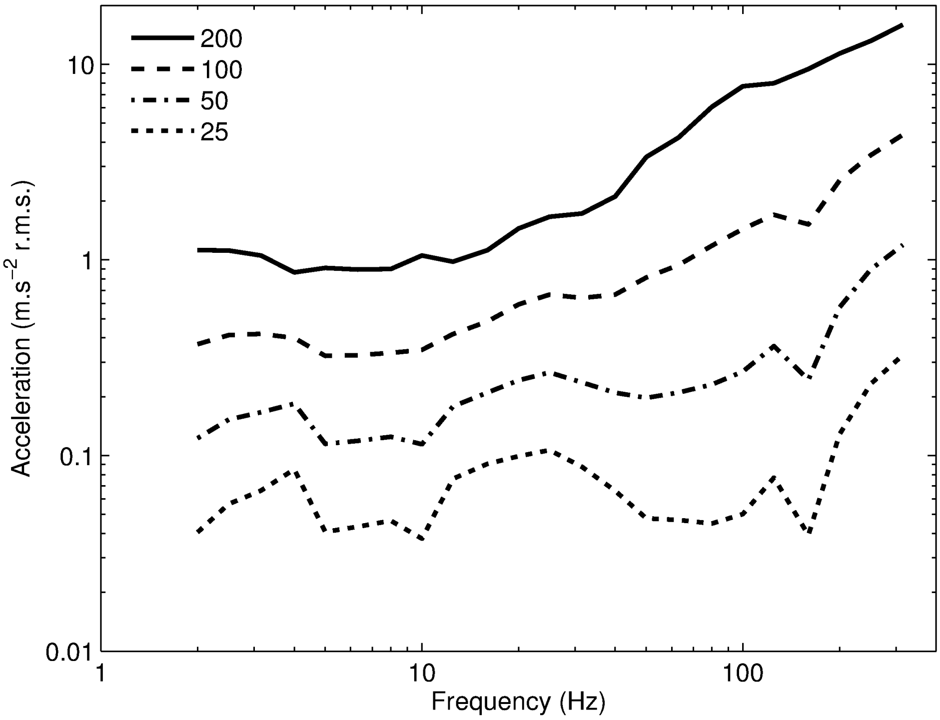


Figure 2.6: Equivalent sensation contours obtained by Morioka and Griffin (2006b) for seated people exposed to vertical vibration. The contours correspond to subjective magnitudes of 25, 50, 100 and 200, relative to a vertical 20-Hz reference motion with magnitude 0.5 m.s$^{-2}$ r.m.s..

With standing subjects, it is likely that, in some conditions, postural instability will occur when the magnitude of low-frequency vibration exceeds a 'stability threshold'; this may cause a magnitude-dependence of the frequency effect, since low-frequency vibration might cause more discomfort than high-frequency vibration at certain magnitudes.

### 2.3.3 The effect of supports on vibration discomfort

Body supports can affect the vibration discomfort of people. This effect has been investigated for seated people, but not for standing people. Paddan and Griffin (1988a, 1988b) showed that a backrest increased the transmission of horizontal vibration to the head of seated people, in particular with fore-and-aft vibration (Paddan and Griffin, 1988b). The authors concluded that this change of vibration transmission was partly due to the additional transmission path for vibration, but also to alteration of the posture, in particular a stiffening of the back, which may alter the resonance frequencies of the body and the forces within the body.

The effect of a backrest on the discomfort of seated people exposed to vibration is summarized in Table 2.4, based on the results of Parsons *et al.* (1982) and Wyllie and Griffin (2007, 2009). Generally, a backrest increases discomfort, possibly due to an increase of vibration at the head and neck (Wyllie and Griffin, 2007). However, the presence of a backrest improved comfort at low frequencies, in particular with fore-and-aft vibration. Wyllie and Griffin (2007, 2009) suggested that this may be due to the backrest preventing amplification of the vibration by the body at frequencies similar to the frequency of natural sway of body.

Table 2.4: Summary of the effect of backrest on the discomfort of seated people. References: [1] Wyllie and Griffin (2007); [2] Wyllie and Griffin (2009); [3] Parsons *et al.* (1982).

| | Around 0.2 Hz | 0.2 Hz to 1.6 Hz | 2 Hz to 60 Hz |
|---|---|---|---|
| Fore-and-aft vibration | Improved comfort[2] | Improved comfort[2] | Increased discomfort (except at 2 Hz)[3] |
| Lateral vibration | Marginally improved comfort[1] | Increased discomfort[1] | Increased discomfort (less than with fore-and-aft vibration)[3] |

### 2.3.4 Waveform

Most studies on vibration discomfort used sinusoidal stimuli (i.e., motions consisting in a single frequency component). This generally allows an atomic and reproductible approach for the investigation of the effect of specific vibration characteristics on discomfort. However, motions experienced in real situations are never sinusoidal, and contain a wider range of frequencies. It is therefore important to know how results obtained for single-frequency motions can be applied to different types of motions, more similar to vibration experienced in real transport environment.

#### 2.3.4.1 Multi-frequency vibration

When a vibration stimulus contains several frequency components, they are likely to interact with each other in the creation of discomfort.

Miwa (1968b) applied to vibration stimuli a model developed by Stevens (1956) for predicting the subjective loudness of acoustic stimuli containing several frequency components. The model is based on the concept of inhibition: due to some frequency components masking other components, the increase of the total discomfort due to the addition of a new component is only a fraction (noted $F$) of the discomfort caused by the additional component when presented alone. Based on this idea, Miwa suggested that the 'Vibration Greatness', VG (which corresponds to the subjective magnitude in the model developed by Miwa, 1967a) of a complex vibration can be estimated with Equation (2.3):

$$\mathrm{VG}_t = (1 - F)\,\mathrm{VG}_m + F\Sigma_i \mathrm{VG}_i \tag{2.3}$$

where:

- $\mathrm{VG}_t$ is the vibration greatness of the complex motion.
- $\mathrm{VG}_m$ is the vibration greatness of the worst frequency component.
- $\Sigma_i \mathrm{VG}_i$ is the sum of the VG of all components.
- $F$ is an inhibition parameter.

Miwa (1968b) found that $F$ was equal, in average, to 0.3. However, the value of the parameter $F$ depended on the separation between the frequencies of the components, and was close to 1.0 (no inhibition) when the frequency difference was sufficient.

This model was compared with other methods of evaluation by Fothergill and Griffin (1977). The method of magnitude production was used to determine the subjective magnitude of complex motions and of each of their components separately. The predicted discomfort of the complex motions, obtained with several methods, were then compared with the actual reported discomfort values.

With the method of magnitude production, each stimulus was presented alternatively with a reference sinusoidal motion, and the magnitude of the reference was adjusted until both stimuli felt equally uncomfortable, at which point the magnitude of the reference was retained as the ‘equivalent magnitude’, which is a measure of discomfort. For any complex motion consisting of two frequency components, the equivalent magnitude of the complex motion was noted $E_t$, and the equivalent magnitudes of each of the two individual frequency components presented separately were noted $E_1$ and $E_2$.

Three prediction methods were compared to predict the equivalent magnitude of complex motions consisting of two frequency components:

- Method 1: linear sum
$$E_t = E_1 + E_2 \tag{2.4}$$
- Method 2: root-sum-of-squares
$$E_t = \sqrt{{E_1}^2 + {E_2}^2} \tag{2.5}$$
- Method 3: inhibition
$$E_t = E_1 + b\,E_2 \tag{2.6}$$

The authors concluded that the root-sum-square method was sufficient. The inhibition method also provided satisfying results with dual-frequency vibration, but was too complicated to use with a greater number of frequency components. These results were in disagreement with the method advocated in the then-current International Standard 2631-1 (1974) which was equivalent to evaluating frequency bands separately, and retaining as discomfort estimate the discomfort caused by the worst frequency band. This method would probably underestimate the discomfort of complex vibration.

#### 2.3.4.2 Random

In real vibration exposure conditions, the vibration does usually not consist of discrete frequency components, but has a broad continuous frequency spectrum. So, a more accurate representation of vibration experienced in transports is achieved with random vibration. It is therefore useful to compare the effect of sinusoidal and random vibrations on discomfort.

Griffin (1976) constructed equivalent sensation contours for seated people exposed to either one-third octave random vibration or sinusoidal vibration at frequencies in the range 3.15 to 20 Hz. The subjects were generally more sensitive to random vibration than sinusoidal vibration (7% in average, i.e. about 0.6 dB), although this difference was only significant at 10 Hz and 12.5 Hz and was small compared to inter-subject differences.

Donati *et al.* (1983) also constructed equivalent sensation contours for sinusoidal and “narrowband” random vibration in the range 2 to 10 Hz. The subjects were sitting on an automotive seat. The results showed that random vibration caused more discomfort than sinusoidal vibration when the r.m.s. magnitude was kept constant. The difference decreased as frequency increased, from about 2 dB at 2 Hz to about 0.5 dB at 10 Hz.

The conclusion that subjects were ‘more sensitive’ to random vibration than to sinusoidal vibration (i.e., when presented at equal r.m.s. magnitudes) came in contradiction with earlier conceptions that the discomfort caused by a vibration could be predicted from the r.m.s. value.

This shows the need for an alternative measure of magnitude which would be suitable for consistently evaluating various types of motion stimuli, including sinusoidal, random, or transient vibration.

#### 2.3.4.3 Shocks and transients in standards

Current standards advocate the use of the root-mean-square (r.m.s.) value of the frequency-weighted acceleration for evaluating the discomfort of seated or standing people exposed to vibration:

$$r.m.s. = \left[ \frac{1}{T} \int_0^T a_w(t)^2 dt \right]^{1/2} \tag{2.7}$$

where $a_w$ is the frequency-weighted acceleration.

It is also suggested that when motions contain shocks or transients, the r.m.s. method might not be optimum. Two additional methods are advocated in ISO 2631-1 (1997): the vibration dose value (VDV, Equation 2.8), and the maximum transient vibration value (MTVV, Equation 2.9), which is the maximum value of the running r.m.s. value:

$$VDV = \left[ \int_0^T a(t)^4 dt \right]^{1/4} \tag{2.8}$$

$$MTVV = \max \left\{ \left[ \frac{1}{\tau} \int_{t_0}^{t_0+\tau} a_w(t)^2 dt \right]^{1/2} \right\}_{t_0=0..T-\tau} \tag{2.9}$$

where $\tau$ is the integration window size, with a recommended value of 1 s. It is recommended in ISO 2631-1 (1997) to use one of these methods instead of the r.m.s. value when the crest factor of the motion is greater than 9.0; however, further in the standard, it is recommended to use additional methods when one of the following criteria is exceeded:

$$\frac{MTVV}{r.m.s.} > 1.5 \tag{2.10}$$

$$\frac{VDV}{r.m.s.\, T^{1/4}} > 1.75 \tag{2.11}$$

British Standard BS 6841 (1987) advocates the use of r.m.s. values for evaluating vibration when the crest factor is less than 6.0. If the crest factor is greater than 6.0 or the vibration contains occasional high peak values, the root-mean-quad (r.m.q.) method is recommended (Equation 2.12)

$$r.m.q. = \left[ \frac{1}{T} \int_0^T a_w(t)^4 dt \right]^{1/4} \tag{2.12}$$

#### 2.3.4.4 Previous studies

Ruffell and Griffin (1995) found that the MTVV method was not adapted to the evaluation of vibration containing shocks, as the recommended value of 1 s for the length of the integration window (ISO 2631-1, 1987) did not seem to be based on experimental evidence, and the adequate time constant seemed to depend on the duration of the transient events. Also, if the MTVV method is used, the predicted discomfort of a vibration motion is independent of the magnitude of vibration outside the worst period of vibration, which may not be reasonable.

This suggests that averaging methods, which take account of the whole vibration exposure rather than the worst period only, may be more appropriate for the evaluation of vibration containing transients.

Griffin and Whitham (1980) investigated the discomfort caused by complex motions consisting of background sinusoidal vibration and a number of transient sinusoidal vibrations. The number of such bumps varied between 1 and 16. The aim of the study was to determine an adequate metric for predicting the discomfort caused by these complex motions. Averaging methods such as the $rm_\lambda$ method (Equation 2.13) were compared with different integer values of $\lambda$, and it was found that a value of 3 or 4 was appropriate.

$$rm_\lambda = \left[ \frac{1}{T} \int_0^T a_w(t)^\lambda dt \right]^{1/\lambda} \tag{2.13}$$

This result was consistent with the results of Howarth and Griffin (1991), which suggested that the r.m.q value (Equation 2.12) was more appropriate to predict the discomfort of complex motions consisting of a random background vibration with various numbers of random shocks than the r.m.s. value, which underestimated the discomfort caused by shocks.

### 2.3.5 Direction

#### 2.3.5.1 Comparison of different axes of vibration

The discomfort of people exposed to fore-and-aft was generally found to be similar to the discomfort caused by lateral vibration, particularly with seated subjects. For example, Miwa (1967a) concluded after preliminary experiments that the discomfort of seated people was the same in the fore-and-aft and lateral directions, so only fore-and-aft vibration was included in all further studies by the same author. Similar results were found by most researchers constructing frequency weightings and equivalent sensation contours.

Standing people may have a different response to fore-and-aft and lateral vibration. Nawayseh and Griffin (2006) investigated the effect of low-frequency random vibration on the loss of balance of standing people (measured for example by the displacement of the centre of balance) and found that the loss of balance was greater with fore-and-aft vibration. However when frequency weightings were constructed for both directions, it was found that the shape of the weightings were similar for both directions. This means that the frequency-dependence of the effect of vibration on balance is the same in fore-and-aft and lateral direction, but that the overall sensitivity is greater in the fore-and-aft direction. This was expected as the base of support is smaller in the fore-and-aft direction than in the lateral direction in a common standing posture.

It is generally not assumed that the discomfort caused by vertical vibration is similar to the discomfort caused by horizontal vibration as the mechanisms of discomfort are likely to be very different.

#### 2.3.5.2 Inter-axis equivalence

Most studies investigating the discomfort of standing people were restricted to vertical vibration (Section 2.3.1.1). In addition, the few studies with horizontal vibration investigated the effect of frequency in each direction of vibration, but did not compare vibration in different axes directly. The reference vibration was not common for all directions of test stimuli, so no inter-axis equivalence could be derived.

Some studies conducted with seated subjects show the relative sensitivity between axes. Griffin *et al.* (1982a), using the method of constant stimuli with 4-seconds sinusoidal vibration, constructed equivalent sensation contours for fore-and-aft, lateral and vertical sinusoidal vibration in the range 1 to 100 Hz. All contours corresponded to the same reference motion (i.e., 10-Hz vertical vibration at magnitude 0.8 m.s$^{-2}$ r.m.s.). The relative sensitivity between axes at all frequencies can be derived by calculating the ratios of the accelerations on the comfort contours in different directions. These ratios are shown in Figure 2.7. For example, $K_x/K_z$ was obtained by dividing the acceleration on the contour for vertical ($z$) vibration by the acceleration on the contour for fore-and-aft ($x$) vibration. A value of $K_x/K_z$ greater than unity at a given frequency means that subjects were more sensitive to fore-and-aft vibration than to lateral vibration.

Similar data were derived from the results of Miwa (1968c), who constructed equivalent sensation contours for fore-and-aft and vertical vibration in the range 3 to 100 Hz. The method of magnitude production with semantic labels was used, therefore no reference vibration was used. The contours correspond to an ‘unpleasant’ level of vibration, and the maximum ‘tolerance’ level.

Mistrot *et al.* (1990) and Griefahn and Bröde (1997) investigated the relative sensitivity to vibration in the three translational axes with similar methods. In both studies, subjects used the method of magnitude production and were asked to adjust the magnitude of a test vibration in the vertical, fore-and-aft or lateral direction, to match the sensation caused by a vertical reference at the same frequency. The method varied only slightly between the studies, as in the study conducted by Mistrot *et al.* (1990), subjects could switch between test and reference as many times as they wished, whereas in the study by Griefahn and Bröde (1997), subjects were only exposed to the reference once, followed by a test which lasted as long as the subjects needed to reach an equal sensation. The relative sensitivities derived from these studies are shown in Figure 2.7.

The relative sensitivities derived with a similar method from the frequency weightings advocated in standards ISO 2631-1 (1997) and BS-6841 (1987) are also shown in Figure 2.7 for comparison. For example, $K_x/K_z$ was calculated from the ratio of the weighting $W_d$ (used for horizontal vibration) to $W_b$ (used for vertical vibration).

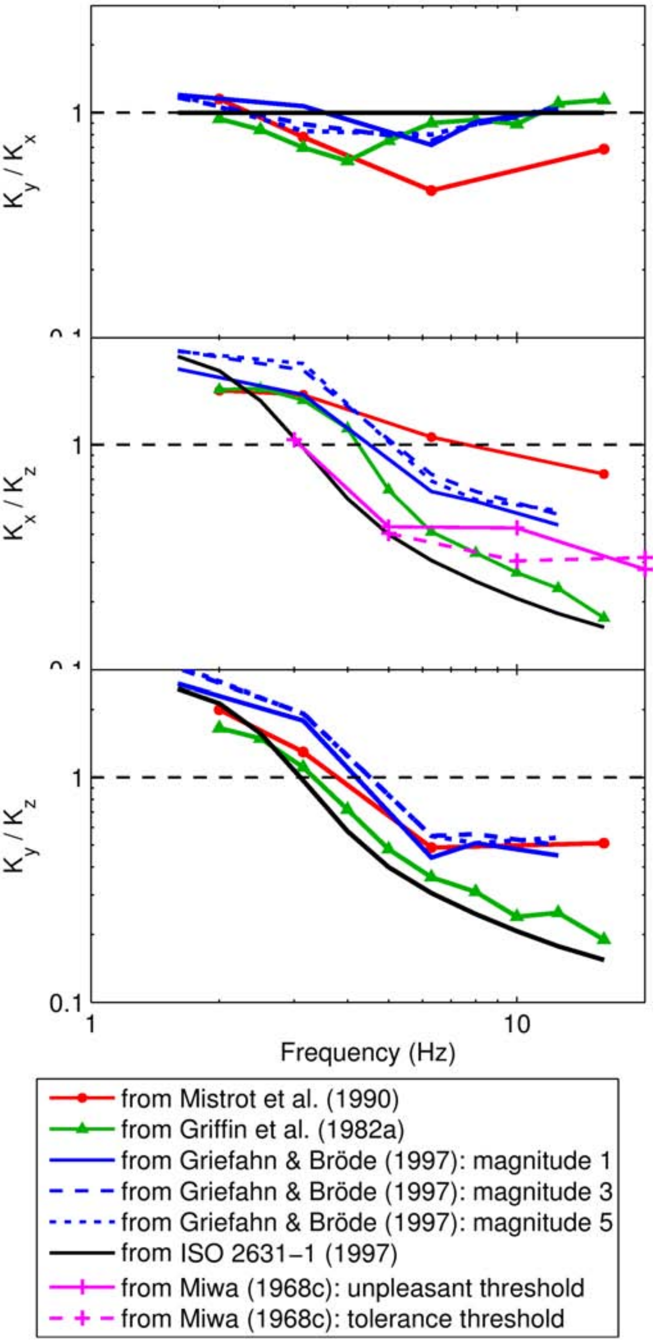


Figure 2.7: Relative sensitivity between directions of vibration, derived from the results of previous studies.

In Figure 2.7, all values of $K_x/K_z$ or $K_y/K_z$ found in previous studies are greater than the values derived from the standards. This suggests that the frequency weightings and multiplying factors advocated in the standards underestimate the sensitivity of seated people to horizontal vibration compared to vertical vibration (or overestimated the sensitivity to vertical vibration). The sensitivity to lateral vibration is also overestimated compared to fore-and-aft vibration.

All studies show a similar trend, where the relative sensitivity between fore-and-aft and lateral vibration is approximately constant with frequency, and the relative sensitivity between horizontal and vertical vibration decreases with increasing frequency over the whole range 2 to 20 Hz. Discrepancies can be observed between the results of different studies, that might be due to the different psychophysical methods used, and the methods used to address subjective biases. For example, in the study by Griefahn and Bröde (1997), the adjusted magnitudes were corrected by a multiplying factor taking account of the fact that, at higher magnitudes of vibration, subjects tended to adjust the test vibration to a level lower than that corresponding to true equivalence. However, the correction factor used for horizontal test motions (following a vertical reference) was based on the bias observed with vertical test motions (also following a vertical reference). The bias may be different whether the reference and test motions are in the same direction or in a different direction. Also, in the cited studies, the reference vibration was always horizontal. Therefore, the measurements of relative sensitivity might be biased by the asymetrical design giving more importance to the fore-and-aft axis of vibration.

### 2.3.6 Duration

It is reasonable to assume that subjects or passengers exposed to vibration for 1 minute would feel more uncomfortable than if they were exposed to the same magnitude of vibration for only a few seconds. This suggests that the discomfort caused by vibration does not only depend on the magnitude, but also on the duration of exposure. This was the subject matter of a number of studies.

#### 2.3.6.1 The effect of duration on the perception threshold

Parsons and Griffin (1988) investigated the effect of the exposure duration on the perception threshold of seated people exposed to vertical vibration. The frequency of vibration was 16 Hz, and the duration of stimuli was 1, 2, 4, 8, 16, 32 or 64 cycles (i.e., 1/16, 1/8, 1/4, 1/2, 1, 2, or 4 seconds respectively). The perception threshold tended to decrease with duration, suggesting the sensitivity increased with duration and longer stimuli were more likely to be perceived. The thresholds for stimuli containing 8 cycles or more (lengths of 0.5 s or more) were significantly lower than the thresholds for stimuli containing 4 cycles or less (shorter than 0.5 s).

#### 2.3.6.2 The effect of duration on discomfort

Griffin and Whitham (1980) found that the discomfort caused by vibration at frequencies 4, 8, 16 and 32 Hz increased with the duration of stimuli. The durations ranged from 1/32 s to 32 s. This result was in agreement with most previous studies on the effect of duration. The authors found that the discomfort caused by vibration stimuli of different durations $T$ was proportional to $T^A$, where $A$ was a constant that was equal to 0.29, 0.35, 0.41 and 0.45 for 4-Hz, 8-Hz, 16-Hz and 32-Hz vibration respectively. In other terms, the discomfort was proportional to $T^{1/\lambda}$, with $\lambda$ equal to 3.5, 2.9, 2.5 and 2.2, for 4-Hz, 8-Hz, 16-Hz and 32-Hz vibration respectively. The authors suggested that the effect could be accounted for by using the vibration dose value (VDV) as an estimate of discomfort. Contrary to the r.m.s value, which is an averaging method and as such does not take into account the duration of the stimuli, the VDV method is a cumulative method:

$$VDV = \left[\int_0^T a(t)^4 dt\right]^{1/4} \tag{2.14}$$

Using the VDV implies that if the magnitude is kept constant, the discomfort caused by vibration is proportional to $T^{1/4}$, where $T$ is the duration of exposure:

$$VDV = \left[T \frac{1}{T} \int_0^T a(t)^4 dt\right]^{1/4} = T^{1/4} \left[\frac{1}{T} \int_0^T a(t)^4 dt\right]^{1/4} \tag{2.15}$$

$$\Rightarrow VDV = T^{1/4} r.m.q. \tag{2.16}$$

This time-dependence is similar to the trend observed in the experiments, although the values for the exponent (equal to 4 in the definition of the VDV) were found to be lower than 4 (between 2.2 and 3.5, depending on the frequency). The exponent of 4 was also found to be more appropriate than an exponent of 2, as in the r.m.s. method advocated in standards, for the evaluation of motions containing transients (Section 2.3.4.4).

#### 2.3.6.3 The effect of duration in standards

Previous versions of International Standard 2631-1 (published in 1974 and 1985) included a time dependency for the effects of vibration on comfort. The current version of the standard ISO 2631-1 (1997) does not include such a dependency any more. In the standard, it is stated: “for specific applications, other standards may include an appropriate time dependence of vibration magnitude and duration”. In BS 6841 (1987), it is suggested that the vibration dose value (VDV) may be used to compare the discomfort caused by vibration motions of different durations, in agreement with the conclusions of previous studies (Section 2.3.6.2).

#### 2.3.6.4 The effect of duration on frequency weightings

In all standards, frequency weightings are recommended for the evaluation of vibration in each direction. The frequency weightings provided do not depend on the duration of vibration. This assumes that the rate at which discomfort increases with duration does not depend on frequency. It is therefore necessary to determine whether the effect of duration depends on frequency to assess the validity of frequency weightings for the evaluation of vibration motions of different durations.

Griffin and Whitham (1980) calculated the rates of growth of discomfort with duration at 4, 8, 16 and 32 Hz, and found different values (0.29, 0.35, 0.41 and 0.45). The systematic increase of the rate of growth with frequency suggests that the difference may not be due to random fluctuations. However, the authors conducted a separate study ('Experiment IV' reported by Griffin and Whitham, 1980) designed to determine whether the effect of duration depends on frequency, and found no significant difference between 4 Hz and 32 Hz. This apparent discrepancy with the different rates of growth found in the other study was attributed to the difference in the experimental design. The study designed specifically to investigate the effect of frequency on duration effect may be more reliable.

Gallais (2008) showed that the shape of comfort contours for seated people exposed to lateral vibration in the frequency range 0.5 to 16 Hz depended on the duration of exposure (Section 8.3 in Gallais, 2008) when the duration of exposure varied between 5 minutes and 30 minutes.

To conclude, it seems that for long durations of exposures (5 to 30 minutes), the frequency weightings depend on the duration, but for exposures of 30 seconds or less, the effect of duration on frequency weightings is less clear.

### 2.3.7 Inter-subject variability

#### 2.3.7.1 Gender

Due do physiological and psychological differences, the response of males and females to vibration may be different. However most studies comparing the response of seated males and females found no differences:

- Griefahn and Bröde (1997) investigated the inter-axis equivalence between the fore-and-aft, lateral and vertical axes with seated men and women, using the method of magnitude production. Twenty-six subjects were used, including 15 males and 11 females. They found no difference between males and females

- The perception thresholds of seated and standing subjects in the frequency range 2 to 63 Hz and vibration in the fore-and-aft, lateral and vertical directions were determined for 18 male and 18 female subjects by Parsons (1988). No differences between the two groups were found.

- Equivalent comfort contours were determined for fore-and-aft, lateral and vertical sinusoidal vibration in the range 1 to 100 Hz by Griffin *et al.* (1982a) with 18 male and 18 female subjects. The contours produced by the males and the females were similar. The method of constant stimuli was used.

- Equivalent comfort contour were determined for vertical sinusoidal vibration in the frequency range 0.5 to 5.0 Hz by Corbridge and Griffin (1986) with 20 male and 20 females subjects. The authors concluded that "the shapes of the equivalent comfort contours were relatively unaffected by subject age or gender".

- Dempsey and Leatherwood (1975), cited by Leatherwood *et al.* (1980), conducted a methodological study which showed that age, weight, and gender did not affect significantly the discomfort response to vibration.

- Spång (1997) investigated the severity of 50 shocks, with 92 subjects (approximately half of which were males) using the method of magnitude estimation without a reference. It appeared that "the relative judgments of the severities of the shocks were not significantly different" between males and females.

- Whitham and Griffin (1978), investigating the location of vibration discomfort in the body for 30 men and 30 women in the frequency range 2 to 64 Hz. There was no notable difference between men and women, except at 4 Hz, where women reported more discomfort in the chest, and men reported more discomfort at the back of the head.

In some of the studies cited in this section, differences were found between males and females in a small number of conditions, although they were judged small and were considered negligible. Also, Landström and Lundström (1986) compared the perception thresholds of standing males and females in the range 1 to 125 Hz. The curves had similar shapes for both genders, but the perception thresholds of females were lower than those of males (by about 2 to 3 dB at most frequencies), suggesting females were more sensitive. However, further analysis showed that the difference of threshold was actually correlated with the body weight of subjects. It was therefore suggested that the threshold depended on the weight of subjects, so the difference in the thresholds between males and females was due to the difference between the average weight between the two groups, and gender itself did not have a major effect on the perception of vibration.

From those studies, it seems that the average response to vibration is similar for males and females. Spång (1997), however, noted that the responses of women showed much more variability than the responses of males, maybe because "women are more variable in terms of where and how the vibrations are experienced". This suggests that using male subjects would provide similar average results as female subjects, but may induce less variability in the data.

#### 2.3.7.2 Age

Similarly to the effect of gender, most studies found that the vibration discomfort of seated subjects did not depend on age. For example, Corbridge and Griffin (1986) found no difference, or negligible differences, between the response to vibration of subjects aged less than 30 and subjects with age greater than 30 (in this study, 20 subjects were aged less than 30 and 20 were aged more than 30). Griffin *et al.* (1982a) investigated the response to vibration of eighteen subjects with age between 19 and 41, and found no significant effect of age.

No study was designed specifically to investigate the effect of age, and subjects with age greater than 40 were rarely used. This is probably justified by the general assumption that vibration discomfort does not vary with age. This may not be true with standing people, as older people may be more subject to loss of balance.

Nawayseh and Griffin (2006) investigated the effect of random motions on loss of balance, using both objective (in particular, the displacement of the centre of pressure, or COP) and subjective (the probability of loss of balance, estimated by the subjects) dependent variables. Twelve subjects aged 24-41 participated in the experiment, and the displacement of the COP was generally correlated with age, although the correlation was never significant. The probability of losing balance was also non-significantly correlated with age in some conditions. This was consistent with the results of Era and Heikkinen (1985) who reported that postural sway increased with age.

Studies of the effect of age on balance show that balance is degraded as age incrases; for example, Choy *et al.* (2003) conducted a study of the postural stability of 453 women aged 20-80 standing with their eyes closed. The authors found that the women in their twenties were less unstable than older women. The effects were significant from 40 years old when a single-limb stance was tested, from 50 years old when subjects were standing on foam, and from 60 years old when standing on a firm surface.

### 2.3.8 Posture: comparison of the discomfort of seated people and standing people

It is useful to know whether posture affects the vibration discomfort of people, and in particular whether the vibration discomfort of standing people is different from the discomfort of seated people. If standing subjects have different responses, the knowledge of vibration discomfort of seated people may not be applied to standing people, and further investigation of the discomfort of standing people is needed.

It is particularly useful to compare the frequency dependence of vibration discomfort of standing and seated people. For comparing comfort contours obtained with seated and standing subjects, it is necessary that the comfort contours were obtained with the same exact method, which usually means that they need to be obtained in the same study, or the same series of studies. If the contours for seated and standing people were obtained with different subjects, inter-subject variability adds up to the effect of posture and, if the number of subjects is too small, may be more important than the effect of posture that is being measured.

In few studies, equivalent comfort contours were constructed for both standing and seated subjects to allow comparison. Chaney (1964, 1965) determined the limit between 'mildly annoying' magnitudes and 'extremely annoying' magnitudes of vertical vibration for standing and seated people in the frequency range 2 to 30 Hz. Jones and Saunders (1972) and Oborne and Boarer (1982a) constructed equivalent sensation contours in both postures, using magnitude production methods. Contours obtained in both postures are shown in Figure 2.8.

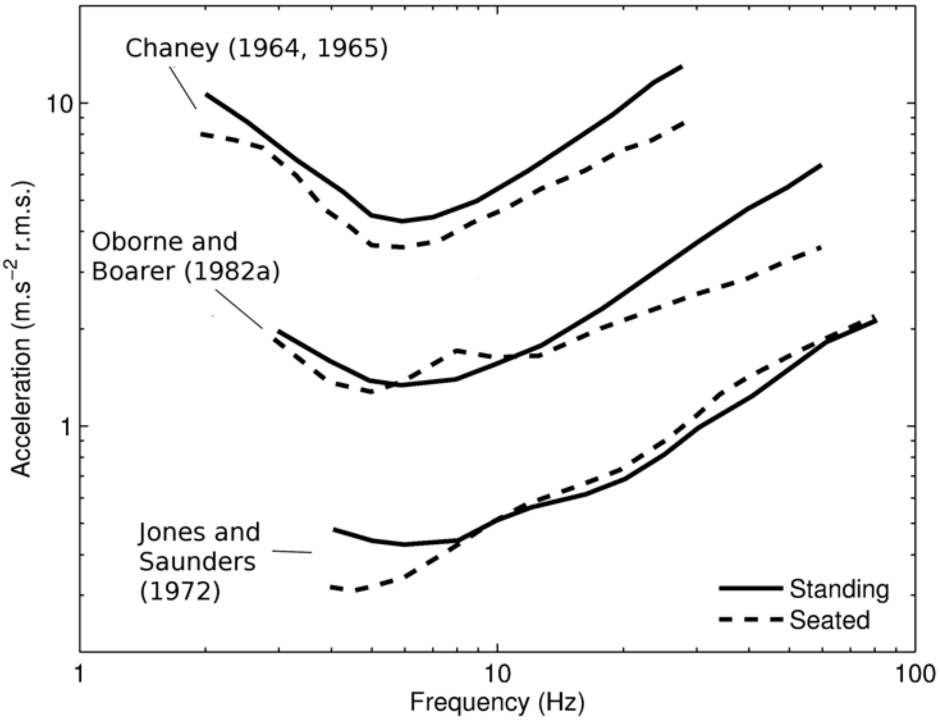


Figure 2.8: Comparison between equivalent sensation contours obtained with standing subjects and seated subjects.

When interpreting the results, it is important to note that the studies by Jones and Saunders (1972) and Oborne and Boarer (1982a) compared vibration with a reference motion presented in the same posture as the test. Therefore, the contours obtained in both postures can be compared in terms of shape, but not in terms of level, as their relative position is arbitrary. Conversely, the method used by Chaney (see Table 2.2) required an absolute assessment of the motions by the subjects, so it allows comparison in terms of level (in

Figure 2.8, the results obtained by Chaney suggest that standing people are less sensitive than seated people to vertical vibration over the range 2 to 30 Hz).

Another difference between the studies was in the choice of subjects. Oborne and Boarer (1982a) used a within-subject design, where the same subjects were exposed to vibration in both postures, whereas in the two other studies, different subjects participated.

Although in all studies, it was found that the contours for standing people were different from the contours for seated people, discrepancies are observed. As suggested by Oborne and Boarer (1982a), these discrepancies may be due to the differences in the design of the studies: subjective methods, choice of subjects, and possibly postures (type of seat, footwear). The study by Oborne and Boarer (1982a) may provide the most reliable comparison, due to its within-subject design.

In any case, there is sufficient evidence that the response of standing people to vibration is different from the response of seated people, and experimental results obtained with seated subjects may not always apply to standing subjects.

## 2.4 Causes of discomfort

### 2.4.1 Localization of discomfort

One possible way for achieving a better understanding of the mechanisms of discomfort is investigating the localization of discomfort or sensations in the body.

Whitham and Griffin (1978) investigated the effect of frequency and magnitude on the location of discomfort experienced by seated subjects exposed to horizontal and vertical vibration in the frequency range 2 to 64 Hz. They found that, during exposure to either fore-and-aft or lateral vibration, discomfort was located in the lower abdomen and buttocks, whereas during exposure to vertical vibration, discomfort arose in the upper torso and at the head, especially at higher frequencies. Vibration magnitude did not have a significant effect on the location of discomfort.

Landström and Lundström (1986) asked subjects exposed to vertical vibration in the standing and seated position to report in which part of the body they felt the vibration. For standing subjects, the sensations resulting from 2-Hz and 8-Hz vibration were located in the whole body, whereas at 31.5 Hz, they were located in the legs and thighs, and at 125 Hz, in the feet only. So, as frequency increased, discomfort was restricted to lower parts of the body. A similar trend was observed with seated people.

### 2.4.2 Relation with the biodynamic response of the body

Discomfort may arise from the perception of vibration in the body (many different perception channels may exist, for example the vestibular system, mechanoreceptors in the skin, mechanoreceptors in the inner organs), so the discomfort experienced by subjects exposed to vibration might be related with the biodynamic response of the body. Establishing the relation between the biodynamic and subjective responses would help predicting the discomfort of people exposed to vibration, as the biodynamic response may be easier to measure than the subjective response, and can be predicted by dynamic models (for example, Coermann, 1962).

#### 2.4.2.1 Driving-point dynamic response

Coermann (1962) hypothesized that the tolerance of seated people to vertical vibration was determined by a ‘physical factor’ such as the transmitted force, the dissipated energy, or the relative displacement of the most effective body masses. These physical factors were calculated with a dynamic model of the body that included two mass-spring systems representing the main mobile parts in the body. The three physical factors are derived from the impedance (i.e., the complex ratio of the transmitted force to the velocity) of the body.

The tolerance threshold of seated people exposed to vertical sinusoidal vibration (i.e., the lowest magnitude at which subject could not tolerate the vibration) were measured by Zeigenruecker and Magid (1959) in the frequency range 1 to 15 Hz. They were compared by Coermann (1962) to curves of constant transmitted force, transmitted energy, and relative displacement of body masses.

The energy and force were not correlated with the tolerance. The comparison between the tolerance curve and a line of constant ‘relative displacement’ is shown in Figure 2.9. The curve of constant relative displacement was similar to the tolerance curve in the frequency ranges 1 to 5 Hz and 10 to 15 Hz, suggesting discomfort may be related with the relative displacement of organs in the body. However in the frequency range 5 to 10 Hz, the tolerance predicted by the relative displacement of masses was higher than the reported tolerance. In the frequency range 5 to 10 Hz, subjects reported pain in the chest, so the author suggested that the tolerance was determined by relative displacement of small organs in the chest, such as the heart. These organs are too small compared to the main body masses to have an influence on the body impedance, so when their vibration determines discomfort, it is not possible to use the body impedance (or any biodynamic indicator derived from the impedance) to predict the tolerance to vibration.

Matsumoto and Griffin (2005) investigated the relation between impedance or apparent mass (i.e., the complex ratio of the transmitted force to the acceleration) and the discomfort of seated subjects exposed to vertical sinusoidal vibration at frequencies 3.15, 4, 5, 6.3

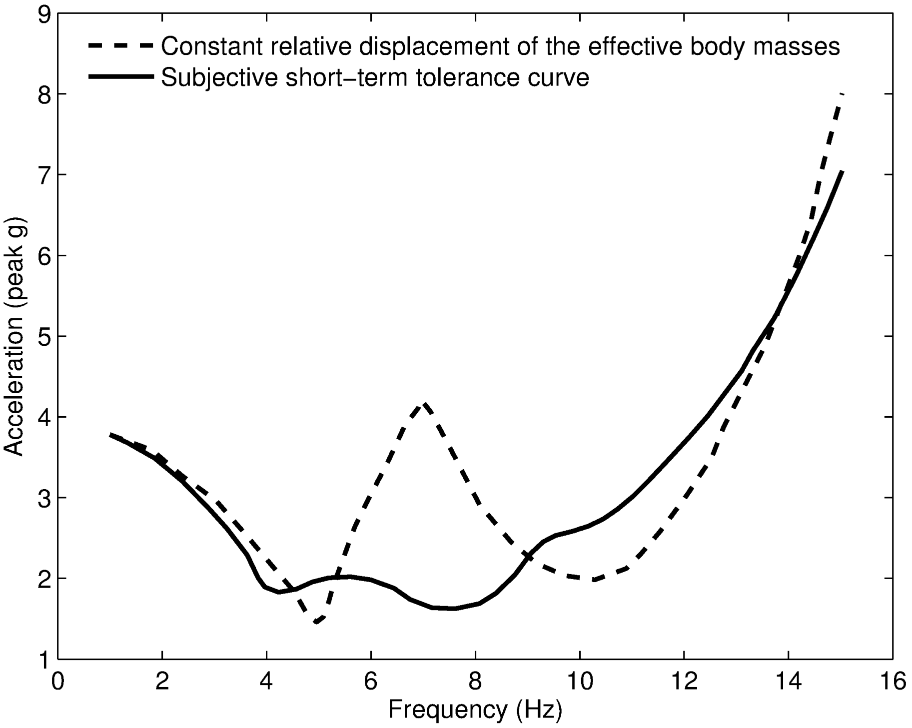


Figure 2.9: Comparison of the short-term tolerance curve to vertical vibration, and a curve of constant relative displacement of effective body masses (from Coermann, 1962).

and 8 Hz. The discomfort experienced by subjects at different magnitudes was correlated with the impedance and apparent mass at lower frequencies (3.15, 4 and 5 Hz), but not at higher frequencies. The authors concluded that neither of the driving-point dynamic responses (impedance or apparent mass) could represent the effect of frequency on vibration discomfort. These responses may represent the effect of magnitude on discomfort at lower frequencies, at which the motions of the different parts of the body occur in phase, but at higher frequencies, the individual responses of body parts may have to be considered to predict discomfort.

#### 2.4.2.2 Transmission of vibration

In many cases, subjects exposed to vibration experience discomfort because some specific body parts are set in motion. The dynamic response of different body parts to whole-body vibration can be represented by the vibration transmissibility, which is the ratio of the vibration of a specific body part to the vibration of the floor (for a standing subject) or the seat (for a seated subject).

Schust *et al.* investigated the relations between transmissibilities in different directions and subjective discomfort in the neck region, and concluded that "the shape of frequency weighting curves derived from intensity judgements of the neck-region showed the most pronounced similarities to the shapes of maxima of the modulus of the transfer functions of the rotation around the y-axis", suggesting that the pitch-pitch transmissibility is related with subjective discomfort.

Paddan and Griffin (1993a, 1993b) measured the floor-to-head transmissibility for standing people exposed to fore-and-aft, lateral and vertical vibration. The vibration was a broad-band random motion (the frequency band was 0.25 to 25 Hz for vertical vibration and 0.06 to 10 Hz for horizontal vibration). Harazin and Grzesik (1998) measured the transmissibility of vertical vibration from the floor to different parts of the body of standing persons. The floor-to-head transmissibility for vertical vibration obtained by Paddan and Griffin (1993a) and the floor-to-head, floor-to-shoulder and floor-to-knee transmissibities obtained by Harazin and Grzesik (1998) are shown in Figure 2.10. The results obtained in both studies are consistent, and show that the transmission of vibration to the head is approximately constant and equal to 1.0 over the range 0 to 15 Hz, and decreases with increasing frequency in the range 15 to 200 Hz. The transmissibility to other parts of the body (knees and shoulders) is greater than 1.0 in the range 0 to 15 Hz, and also decreases with increasing frequencies in the range 15 to 200 Hz.

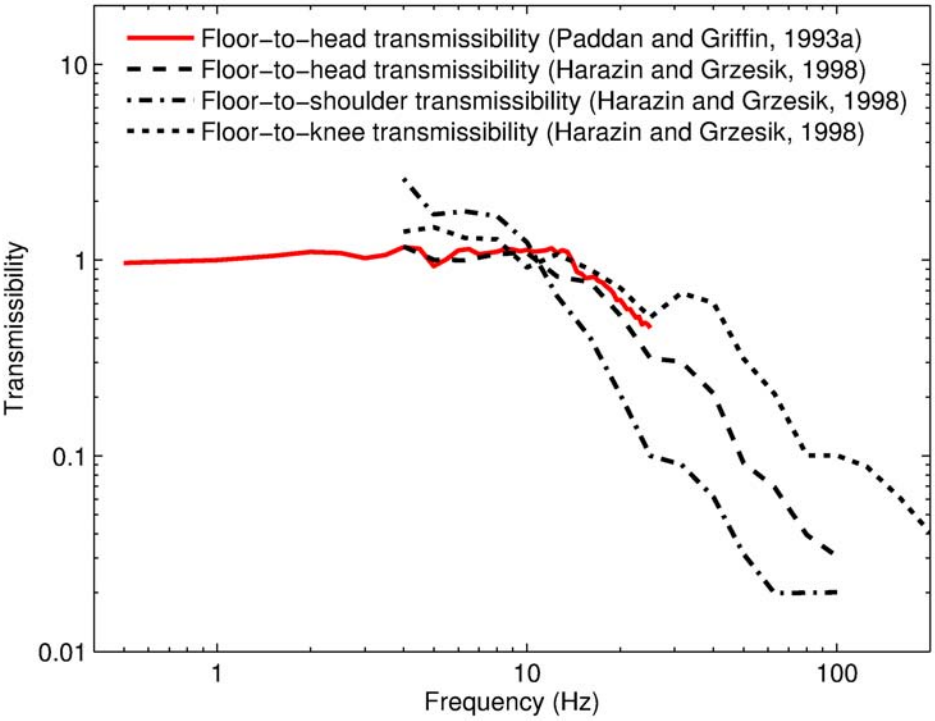


Figure 2.10: Transmissibility measured with standing people exposed to vertical vibration.

The transmissibility can be compared with the location of discomfort in the body of standing people exposed to vertical vibration, reported by Landström and Lundström (1986). At 2 and 8 Hz, subjects experienced discomfort in the whole body, and as frequency increased from 8 to 125 Hz, the discomfort became restricted to lower parts of the body (the feet and legs at 31.5 Hz, and the feet at 125 Hz). This suggests that discomfort may be experienced in a specific part of the body when a sufficient amount of vibration is transmitted to this body part. For example, discomfort was experienced in the torso only at 2 and 8 Hz, where the transmissibility to the shoulders is between 1.0 and 2.0 (Harazin and Grzesik, 1998). At 31.5 Hz and 125 Hz, where the transmissibility to the shoulders is about 0.1 and 0.02 respectively (Harazin and Grzesik, 1998), no discomfort was experienced in the shoulder. So, the transmissibility may be used to estimate the areas of the body where discomfort is experienced; however, this does not indicate that the discomfort magnitude can be predicted quantitatively from the transmissibility.

Griffin *et al.* (1982a) investigated the relation between the seat-to-head vibration transmissibility and the discomfort magnitude experienced by seated people, and concluded that at some frequencies, the discomfort was correlated with the transmissibility. However, the transmissibility was different for men and women, but equivalent comfort contours constructed for both groups were very similar. This suggested that the transmissibility was not sufficient for predicting the discomfort. A similar conclusion had been reached by Oborne and Boarer (1982b), who observed that the equivalent comfort contours obtained with subjects sitting in an upright posture and in a slouched posture were similar, although the seat-to-head transmissibility differed between the two postures.

#### 2.4.2.3 Internal forces

Schust *et al.* (2009) attempted to relate subjective discomfort of seated people exposed to vibration to spinal forces caused by vibration, which were calculated with finite element simulations. The authors compared the correlation between spinal forces and subjective judgements to the correlation between the 'vibration total value' (an indicator derived from the acceleration magnitude) and the subjective judgements. The correlation with the spinal forces was "at least as good" as the correlation with the vibration total value suggesting that the magnitude of sensation "reflect to a certain extent the effects of objective parameters like transfer functions or calculated internal forces".

### 2.4.3 Postural stability

#### 2.4.3.1 Brief overview of models

Many studies have been carried out on the subject of postural stability. This is a complex problem, because, when submitted to a perturbation, the body uses various strategies to maintain balance. Thus, it should be treated as an active system. Different models of postural stability have been developed for different purposes:

- Conceptual models (e.g. Agarwal, 1970) focus on the analysis of the flow of information between the sensory system, the central nervous system, and the skeletal muscle system, which are the different links of the balance system. They may help understanding of the underlying mechanisms of balance-maintaining, but do not quantify the reactions of the body.

- The simplest mechanical model is based on the concept of ‘motion induced interruptions’ (MII). This model was developed by Graham (1990) to evaluate the problems related to loss of balance on ships, and is referred to as the ‘Graham model’, or ‘rigid body model’. A rigid body, with mechanical characteristics representative of those of a real human body, is used. An ‘interruption’ happens when the subject, exposed to vibration of the floor, has to adjust stance or grab a support to maintain balance, and thus has to interrupt current activities (walking, lifting, reading, etc.). The model predicts that a MII occurs whenever the forces are large enough to overturn the rigid body representing the human body.
- Some passive models with several rigid links have been developed (see, for example, Kodde *et al.*, 1982; Koozekanani *et al.*, 1980). Lewis and Griffin (1995) suggested that passive biomechanical models can help to understand the relationships between the motion of the body, the forces within the musculo-skeletal system and the reaction forces with the supporting surface, but cannot predict the loss of balance in all conditions, since the postural active control system cannot be represented accurately with a passive system.
- Active biomechanical models, more liable to predict loss of balance in different conditions, have been developed (e.g., Johansson and Magnusson, 1988). These models may give a better understanding of the relations between torques at the joints and movements of the body. A model of linear transfer functions has been developed by Maki (1986). The author made direct measurements of the transfer functions between the floor acceleration and the displacement of the centre of pressure (COP). They found that the gain of the function depended on the magnitude of motion. Maki *et al.* (1987) presented a model which added a saturation nonlinearity to the linear transfer function.

#### 2.4.3.2 Experimental measurement of loss of balance

Nawayseh and Griffin (2006) conducted a study of the postural stability of standing subjects exposed separately to lateral, fore-and-aft, pitch, and roll random (one-third octave band) oscillation. They used two types of dependent variables:

- Objective measurements: the percentage of subjects who lost balance and the displacement of the centre of pressure were measured.
- Subjective variables: the subjects were asked, after a stimulus was presented, to state the probability that they would lose their balance if the same exposure was repeated.

Frequency weightings were derived from the results. For this purpose, the authors chose to use the subjective variables, considering that weightings should reflect perception. In fact, motion-induced interruptions, which are the main source of discomfort, are triggered by the perception of instability, rather than by actual falls. Weightings based on actual risk of fall, which may be used to assess risks of injuries, may be different.

The authors also concluded that the transfer function between excitation magnitude and COP displacement was nonlinear (the gain decreased as the magnitude increased), as Maki (1986) reported.

The results also showed that fore-and-aft and pitch oscillations were more liable to cause loss of balance than, respectively, lateral and roll oscillations; this result was observed with a normal standing posture (240 mm separation between the feet) and may vary with the position of the feet, which define the base of support.

When subjects were exposed to translational vibration stimuli at different frequencies of equal r.m.s. velocity in the range 0.125 to 2 Hz, all measures of postural instability variables peaked around 0.5 Hz. For rotational excitations of equal r.m.s. displacement, the instability was maximal at higher frequencies.

#### 2.4.3.3 The effect of support

Robert (2006) investigated the effect of body supports on balance loss and recovery for standing subjects exposed to shock motions. The body supports used in the experiment were a vertical bar and a backrest against which the subjects leaned their lower back (the motion was then in the fore-and-aft direction). The author found that these two supports had different effects on postural stability. The subjects were asked to rate the level of unbalance they felt, and the 'efficiency' of each supporting device (the term 'efficiency' was not defined explicitly, but was implicitly referring to the efficiency as support, in relation with loss of balance). The bar appeared to be the most 'efficient' support, whereas the support providing the lowest feeling of unbalance was the back support. The correlation between the two indicators, 'unbalance' and 'efficiency', was low ($R^2$=0.06), suggesting they represent two unrelated effects. This low correlation was explained by a fundamental difference between the effects of the two supports: a backrest prevented loss of balance for stimuli of small magnitude (it extended the zone of stability in the initial posture), but if the magnitude was sufficient to induce a loss of balance (if it brought the subject out of the zone of stability), the support could not prevent a fall. Conversely, the bar did not improve stability in the initial posture but, in case of a loss of balance, it helped to recover stability.

As a consequence, the best rated situation (in terms of stability) was with low motion and back support. In a survey conducted by Robert (2006), subjects stated that, apart from being seated, their preferred posture in public transport was standing with a back support.

This is because most perturbations in transports are small, so a back support brings more stability and more static comfort, despite its low ‘efficiency’ compared to holding a bar.

## 2.5 Prediction of vibration discomfort

### 2.5.1 Multi-axis inputs

#### 2.5.1.1 Discomfort of seated people exposed to dual-axis vibration

Several studies were designed to investigate the discomfort experienced by seated people exposed to dual-axis vibration, but the discomfort of standing people exposed to multi-axis vibration has not been investigated. Therefore, all studies cited in this section were conducted with seated people.

Griffin and Whitham (1977) investigated the discomfort caused by simultaneous vertical and lateral 3.15-Hz sinusoidal vibration. The method of magnitude production was used, where subjects were asked to adjust the magnitude of a dual-axis test motion until it caused discomfort similar to that of a single-axis (vertical or lateral) reference motion. The discomfort caused by the stimuli was measured by their ‘vertical equivalent acceleration’ or ‘lateral equivalent acceleration’, i.e. the magnitude of single-axis vibration (respectively, vertical or lateral) that causes an equivalent discomfort. The objective was to compare methods for predicting the equivalent magnitude of a dual-axis motion, $E_t$, from the equivalent magnitudes of the single-axis components, $E_y$ and $E_z$. Several summation methods were compared, based on the models used for the evaluation of multi-frequency motions (Section 2.3.4.1):

- The worst component:

$$E_t = \max(E_y, E_z) \tag{2.17}$$

- The root-sum-of-squares

$$E_t = \sqrt{{E_y}^2 + {E_z}^2} \tag{2.18}$$

- The concept of masking:

$$E_t = E_1 + F\,E_2 \tag{2.19}$$

where $E_1$ and $E_2$ are, respectively, the equivalent magnitude of the most uncomfortable and the least uncomfortable component, and $F$ is a masking coefficient.

The ‘worst component’ method was underestimating the discomfort of dual-axis motions. The masking model, once the parameter optimized, were fitting the data slightly better than the root-sum-of-squares, which was expected because the parameter $F$ was optimized to fit the data. However the root-sum-of-squares provided very satisfying results, and is more suited to practical use, so it was recommended.

Following the study by Griffin and Whitham (1977), Shoenberger (1987, 1988) used a similar method based on magnitude production to compare the equivalent magnitude of dual-axis ($x+z$ and $y+z$) vibration with the equivalent magnitudes of its components. In the study by Griffin and Whitham (1977), one of the components of the dual-axis motion was in the same direction as the reference, and it was observed that this seemed to bias the responses as subjects gave more importance to that component. To avoid such bias, Shoenberger (1987, 1988) used a reference motion in the orthogonal direction, so that no component of the test motion was in the same direction as the reference. The author only concluded that a summation was occuring, as the equivalent magnitude of the dual-axis motions was greater than the equivalent magnitudes of its components. This suggested the need for a summation method but did not provide one. Additionally, only one magnitude ratio between the two components of dual-axis motions was used (1:1), so the scope of the study remains limited.

Mistrot *et al.* (1990) used a similar method to investigate the discomfort caused by dual-axis ($x+z$ and $y+z$) vibration. The main difference with the method used by Griffin and Whitham (1977) was that the subjects were asked to adjust the magnitude of one chosen component of the dual-axis vibration (the component orthogonal to the single-axis reference) until the dual-axis motion caused equivalent sensation to a single-axis reference vibration. In the study by Griffin and Whitham (1977), the subjects were asked to adjust the magnitude of the single-axis motion until it causes equivalent discomfort to a dual-axis vibration. Sinusoidal in-phase vibration at frequencies 3.15 and 6.3 Hz were used. The objective, similarly to the study by Griffin and Whitham (1977), was to determine a method for predicting the equivalent magnitude of dual-axis vibration from the equivalent magnitudes of its single-axis components using a power-summation method:

$$E_t = ({E_y}^b + {E_z}^b)^{1/b} \tag{2.20}$$

It was found that when the exponent $b$ was 1, 3, 4, 5 or $\infty$, the predictions were significantly different from the results. When the exponent was equal to 2, no significant difference was found. This is consistent with the results of Griffin and Whitham (1977) and suggests that the root-sum-of-squares (Equation 2.22) of the weighted accelerations in all directions provides a good estimate of the discomfort caused by dual-axis vibration of seated people.

Dickey *et al.* (2007) compared the discomfort of multi-axis motions, including dual-axis, tri-axis, and 6-axis motions (that included rotations), with the predictions obtained with the method recommended in International Standard ISO 2631:

$$VTV = \sqrt{{k_x}^2{a_{wx}}^2 + {k_y}^2{a_{wy}}^2 + {k_z}^2{a_{wz}}^2 + {k_{e,roll}}^2{a_{w,roll}}^2 + {k_{e,pitch}}^2{a_{w,pitch}}^2 + {k_{e,yaw}}^2{a_{w,yaw}}^2} \tag{2.21}$$

where:

- $VTV$ is the vibration total value, i.e. the estimate of discomfort
- $k_x$, $k_y$, $k_z$, $k_{e,roll}$, $k_{e,pitch}$ and $k_{e,yaw}$ are axis weightings for which values are recommended in the standard (ISO 2631-1, 1997, Section 8.2.2.2)
- $a_{wx}$, $a_{wy}$, $a_{wz}$, $a_{w,roll}$, $a_{w,pitch}$ and $a_{w,yaw}$ are the frequency-weighted accelerations in each direction.

A very low correlation was found between the predicted VTV and the reported discomfort of multi-axis motions. It was concluded that the method recommended in the standards for multi-axis vibration is not adequate and needs revising. However the experimental design did not allow to determine whether the discrepancies between predictions and measurements were due to wrong axis weightings, $k$, or to the root-sum-of-square summation method not being appropriate. These are two separate problems, so the conclusion of the study may not be practically useful.

Fairley and Griffin (1988) determined a method for predicting the discomfort of dual-axis vibration ($x + z$) with a similar method, but using a different approach. The study was designed to establish a relation between the subjective magnitude (i.e., the discomfort) of the dual-axis motion and the subjective magnitude of its components. The studies by Mistrot *et al.* (1990) and Griffin and Whitham (1977) were designed to establish a relation between the equivalent magnitudes, rather than the subjective magnitudes. The difference between subjective magnitude (discomfort) and equivalent magnitude (acceleration) lies in Stevens' power law (Section 2.2.3.1), which predicts that the subjective magnitude depends on the physical magnitude according to a power law. If the exponent in this power law is different from 1.0, the subjective and equivalent magnitudes are not linearly related.

Fairley and Griffin (1988) hypothesized that a power summation method could be used to predict the discomfort of a dual-axis motion from the discomfort of its single-axis components (Equation 2.20), which can be written:

$$\psi_t = \left({\psi_x}^b + {\psi_z}^b\right)^{1/b} \tag{2.22}$$

where:

- $\psi_t$ is the discomfort caused by the dual-axis vibration
- $\psi_x$ and $\psi_z$ are the discomfort caused by, respectively, the fore-and-aft and the vertical component
- $b$ is an exponent to determined

The optimal exponent was found to be around 2, with no significant difference as the vibration frequency varied from 2.5 Hz to 10 Hz. The linear sum method ($b = 1$) was found to overestimate, and the 'worst component' to underestimate, dual-axis discomfort. Because of the difference in the designs, these values of exponent do not have the same signification as the exponents found by Mistrot *et al.* and Griffin and Whitham (1977). However, the difference was overlooked by Fairley and Griffin (1988) who assumed that the discomfort was linearly related to the vibration magnitude.

#### 2.5.1.2 The effect of phase

The discomfort caused by multi-axis vibration may not only depend on the magnitude of the components, but also on the phase relationships between the components. For example, if sinusoidal motions with the same frequency are presented simultaneously in the fore-and-aft and lateral direction, the phase lag between the two components determines the trajectory of the motion, which can be linear (if phase lag is 0°), circular (90°) or elliptical (other values of phase lag). It is therefore important to determine the effect of phase on the discomfort caused by multi-axis vibration motions.

The effect of phase difference between the components of a dual-axis vibrations was investigated by Griffin and Whitham (1977). The authors concluded that the discomfort produced by simultaneous 3.15-Hz vertical and lateral vibration did not vary greatly whether the two components were in phase or with a 90°phase difference. Any other phase difference can be expected to be an intermediate situation between 0°and 90°, so this suggests that discomfort would not vary with phase. This is particularly true at frequencies greater than 3.15 Hz, where phase lags induced by the body depend largely on the subjects, the frequency and the direction, so the mean effect of phase is null. This is consistent with the conclusions of Shoenberger (1987), who found that when seated subjects were exposed to simultaneous vertical and lateral vibration with phase lags 0°, 90°, 180°and 270°at frequencies 3.2, 5 and 8 Hz, discomfort was independent of phase.

However, Shoenberger (1988) found that the discomfort caused by simultaneous fore-and-aft and vertical vibration depended on the phase lag.

### 2.5.2 Prediction methods recommended in standards

The current standards (ISO 2631-1, 1997; BS 6841, 1987) provide evaluation methods for predicting the discomfort of standing people exposed to translational vibration.

The first step of the evaluation of a vibration motion is the frequency-weighting of the single-axis vibration components. For this purpose, frequency weightings are advocated in the standards. In ISO 2631-1 (1997) and BS 6841 (1987), the frequency weighting $W_d$ is recommended for horizontal vibration (fore-and-aft and lateral). For vertical vibration,

$W_b$ is recommended in BS 6841 (1987) and ENV 12299 (1999), and $W_k$ (which is similar to $W_b$) is recommended by ISO 2631-1, although this recommendation is ambiguous since it is also stated in ISO 2631-1 (1997, Annex C 2.2.1 , 'Note') that "for the evaluation of comfort in some environments, e.g. rail vehicles, a frequency weighting, designated $W_b$ (...) is considered the appropriate weighting curve". In addition, it is stated in ISO-2631-4 (2001), which is specific to railway applications, that "$W_b$ is of particular value in the assessment of comfort in rail vehicles". The frequency weightings are defined with analogue filters (transfer functions) in the standards. $W_d$, $W_b$ and $W_k$ are shown in Figure 2.11.

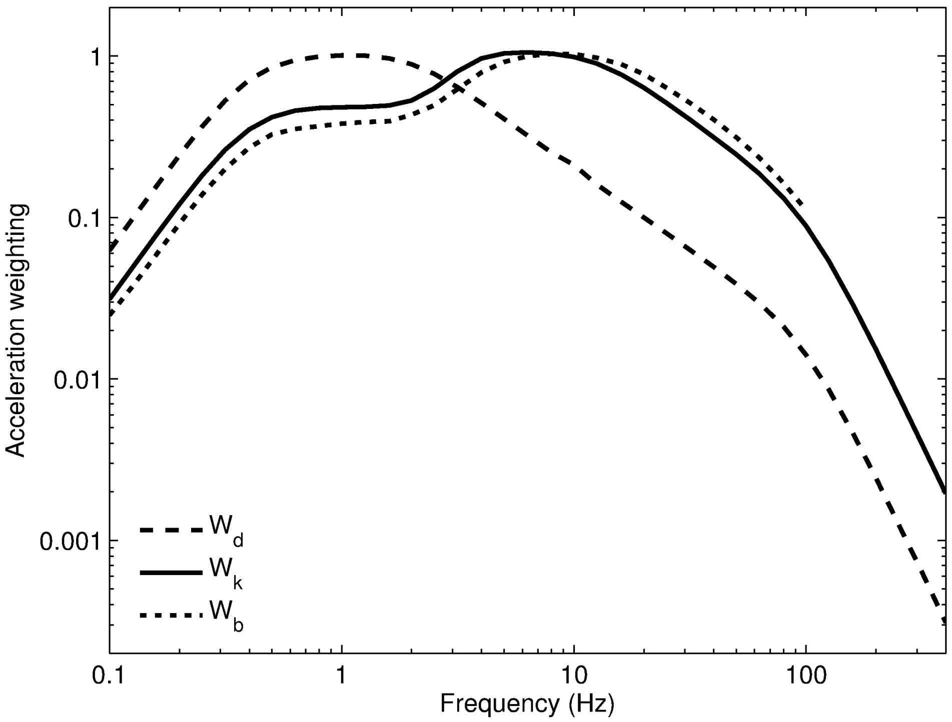


Figure 2.11: Frequency weightings recommended in standards for the comfort of standing people ($W_d$ for horizontal vibration, $W_b$ and $W_k$ for vertical vibration).

After all components have been frequency-weighted, each component may be evaluated. A 'basic' evaluation method is provided for this purpose, based on the root-mean-square (r.m.s.) value (ISO 2631-1, 1997, Section 6.1):

$$a_w = \left[ \frac{1}{T} \int_0^T a_w(t)^2 dt \right]^{1/2} \tag{2.23}$$

where:

- $a_w$ is the weighted r.m.s. acceleration
- $a_w(t)$ is the weighted acceleration
- $T$ is the duration of the measurement

In some cases, this basic evaluation method may not be appropriate and alternative methods are provided (see Section 2.5.3.1).

Finally, the overall discomfort can be estimated using the 'vibration total value', VTV (ISO 2631-1, 1997, Section 6.5) :

$$a_v = \left({k_x}^2{a_{wx}}^2 + {k_y}^2{a_{wy}}^2 + {k_z}^2{a_{wz}}^2\right)^{1/2} \tag{2.24}$$

where:

- $a_v$ is the vibration total value (VTV)
- $k_x$, $k_y$, and $k_z$ are multiplying factors, all equal to 1.0 for the discomfort of standing people
- $a_{wx}$, $a_{wy}$ and $a_{wz}$ are the weighted r.m.s. accelerations in the fore-and-aft, lateral and vertical directions respectively.

Practically, the VTV is equal to the root-sum-of-squares of the r.m.s. accelerations in the three axes of translation.

Rotations are included in the evaluation of vibration for seated people, but not for standing people (ISO 2631-1, 1997, Section 8.2.2.1, Note 3, and Section 8.2.3, Note 2).

Both standards also provide an assessment scale, which describes the expected sensation magnitude of people exposed to vibration as a function of the vibration total value (ISO 2631-1, 1997) or the frequency-weighted r.m.s. acceleration (BS 6841, 1987). The scale is shown in Table 2.5.

Table 2.5: Assessment scale provided in ISO 2631-1 (1997), Section C.2.3 and BS 6841 (1987), Section C.2.1.3.

| **VTV or Weighted r.m.s. acceleration** | **Sensation** |
|---|---|
| $< 0.315$ m.s$^{-2}$ | Not uncomfortable |
| 0.315 - 0.63 m.s$^{-2}$ | A little uncomfortable |
| 0.5 - 1 m.s$^{-2}$ | Fairly uncomfortable |
| 0.8 - 1.6 m.s$^{-2}$ | Uncomfortable |
| 1.25 - 2.5 m.s$^{-2}$ | Very uncomfortable |
| $> 2$ m.s$^{-2}$ | Extremely uncomfortable |

### 2.5.3 Limitations of standards

#### 2.5.3.1 Evaluation of motions containing transients

The basic method exposed in Section 2.5.2, using the root-mean-square value, is probably not suitable for the evaluation of motions containing transients. In the standards, alternative methods are provided for the evaluation of motions that may contain transients.

In ISO 2631-1 (1997), two alternative methods are suggested:

- the vibration dose value, VDV (ISO 2631-1, 1997, Section 6.3.2):

$$VDV = \left[\int_0^T a_w(t)^4 dt\right]^{1/4} \tag{2.25}$$

- the maximum transient vibration value, MTVV (ISO 2631-1, 1997, Section 6.3.1):

$$MTVV = \max\left\{\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w(t)^2 dt\right]^{1/2}\right\}_{t_0=\tau..T} \tag{2.26}$$

  where:

  - $a_w(t)$is the weighted acceleration
  - $T$ is the length of the measurement period
  - $\tau$ is the size of the integration window, for which the recommended value is 1 s.

It is recommended in ISO 2631-1 that one of those alternative methods are used when the crest factor (the ratio of the peak acceleration to the r.m.s. acceleration) is greater than 9.0. The MTVV may also be used when the criterion in Equation (2.27) is verified, and the VDV may be used when the criterion in Equation (2.28) is verified (ISO 2631-1, 1997, Section 6.3.3):

$$\frac{MTVV}{r.m.s.} > 1.5 \tag{2.27}$$

$$\frac{VDV}{r.m.s. \times T^{1/4}} > 1.75 \tag{2.28}$$

This suggests that the alternate methods should be used instead of the r.m.s. when they yield a significantly different value (from the r.m.s.). It is not clear why the alternative method could not also be used when they provide values similar to the r.m.s value, as this would be equivalent to using the r.m.s. method. Using the same method for all vibration would avoid the problems related with the discontinuity resulting from the definition of finite ‘thresholds’ as in Equations (2.27) and (2.28). For example, a vibration motion for which:

$$\frac{MTVV}{r.m.s.} = 1.45 \tag{2.29}$$

would be evaluated with the r.m.s. value, whereas a very similar vibration motion for which:

$$\frac{MTVV}{r.m.s.} = 1.55 \tag{2.30}$$

would be evaluated with the MTVV, which would be about 1.5 times as high as the r.m.s. value. So the evaluation of the second motion would be 1.5 as high as the evaluation of the first motion, although they were very similar.

In a note to Section 4.2.2 of BS 6841 (1987), the r.m.s. method is recommended if the crest factor is less than 6.0, but “when either the crest factors exceed 6.0, or the vibration has variable magnitude, or the motion contains occasional peaks, or the motion is intermittent, the vibration dose value procedure (...) should be used.”

So the recommendations for the choice of a method for evaluating vibration containing transients are ambiguous, and vary from one standard to another.

#### 2.5.3.2 The effect of duration

No method is included in ISO 2631-1 (1997) for taking into account the effect of exposure duration on discomfort (Section 2.3.6.3). However it is recommended in Section C.2.1.2 of BS 6841 (1987) that the VDV method may be used to compare vibration motions of different durations.

### 2.5.4 Criticisms against standards in literature

Oborne (1983) reviewed the then-current standard for the evaluation of the effect of whole-body vibration, ISO 2631-1 (1974). Criticisms were raised on several aspects of the standard, some of which may apply to more recent versions of the standard. In particular, a time-dependency was advocated in the standard, which seemed to be based on a very restricted number of studies; furthermore, in none of those studies, subject experienced vibration for long periods. Any time-dependence found in those studies was derived by interpolation, mathematical modelling or subjects’ estimation of the period over which they could endure the vibration. In any case, the method used to derived a time dependency from those studies was not explicitely stated in the standard.

Another weakness pointed by Oborne (1983) in the standard was the definition of frequency-weighting curves. The author noted that it was “difficult to discern from the document which studies played what part in shaping the committee’s judgment“. The frequency weightings for lateral vibration were essentially based on the work by Dieckman (1958b) and Miwa (1967a), which were based on results obtained with a small number of subjects (Miwa, 1967a, used 10 subjects). Vertical frequency weightings had more experimental support, although the weighting at frequencies greater than 8 Hz was based on a biodynamic model which assumed a single resonance, despite the existence of more resonance frequencies in this range.

Oborne (1983) also noticed that the shape of equivalent sensation contours may vary with magnitude (see Section 2.3.2), and that this effect of magnitude was not taken into account in the standard, where the frequency weightings do not depend on the magnitude.

Griffin (1998) conducted a systematic assessment of the standards related with the effects of whole-body vibration on health. The standards (in particular, ISO 2631-1, 1997 and BS 6841, 1987) include recommendations for the evaluation of vibration in terms of health and comfort; some of the criticism raised about the 'health' evaluation may also apply to the 'comfort' evaluation.

One of the main criticism against ISO 2631-1 was the ambiguity of its recommendations for the evaluation of transient motions (see Section 2.5.3.1). Four methods are considered for the evaluation of vibration (r.m.s., MTVV, VDV, and eVDV, defined in Equation 2.31 and Section C.2.2.2 of ISO 2631-1, 1997), and the criteria for choosing one method or another are vague and inconsistent. In one section of the standard, it is stated that alternative methods (MTVV or VDV) should be used if the crest factor is greater than 9.0 (in BS 6841, 1987, this threshold is set at 6.0), which seems excessive, and not consistent with the other criteria defined further in the standard (Equations 2.27 and 2.28).

$$eVDV = 1.4\, a_w\, T^{1/4} \tag{2.31}$$

where $a_w$ is the weighted r.m.s. value, and $T$ is the length of the measurement period.

Griffin (1998) also pointed out that "at the limiting criterion for using MTVV or r.m.s. the error obtained by choosing one or the other is 50%" (and 25% in the case of VDV), suggesting that an undesirable discontinuity in the evaluation procedure is created.Other criticisms include the definition of the MTVV method, for which the choice of the time constant is not based on any experimental evidence.

Also, it is not clear on which experimental evidence the weighting $W_k$ (advocated for the evaluation of vertical vibration) was constructed, and $W_k$ is "almost within the error tolerance of existing weighting $W_b$", so its introduction may not be justified.

Finally, it is explained in an annex to the standard that "there is only limited experience in applying this part of ISO 2361 (...) for all axes of standing, reclining and recumbent positions", which is ambiguous and suggests that the recommendation may not be valid for standing people, since it was mainly based on experimental evidence obtained with seated subjects.

Lewis and Griffin (1998) compared the results obtained by evaluating vibration recorded in different types of vehicles (mostly road and industrial vehicles) with the different methods advocated in the standards. The authors found that the weighted r.m.s. acceleration obtained according to ISO 2631-1, 1997, and BS 6841, 1987, differed by about 14% due to different frequency weightings. The evaluation of motions containing repeated shocks according to ISO 2631-1 was not straight forward due to the number of alternative methods suggested in the standard, which provided very different results.

Lewis and Griffin (1998) also found that the estimated vibration dose value (eVDV, Equation 2.31) underestimated the VDV value derived from the fourth power of the acceleration by about 40% in some cases. Howarth (2004) made a similar observation with railway vibration.

## 2.6 Conclusion

It appears that vibration is an important cause of discomfort for passengers in public transport, as it affects the passengers opinion about the travel experience and their future choice of a transport mode. It is therefore important for transport operators to take vibration discomfort into account.

Current International and British standards include methods for predicting vibration discomfort, but it seems they are not always satisfactory, and their applicability to standing people is uncertain. Indeed, they were based on knowledge of vibration discomfort of seated people. Since it has been shown that, in particular, the frequency-dependence of vibration discomfort depends on the posture (seated or standing), methods advocated in the standards may not be appropriate for standing people.

Equivalent comfort contours showing the effect of the frequency of vibration on the vibration discomfort of standing people have been constructed in several studies, generally with vertical vibration and at frequencies greater than about 3 Hz. The effect of the frequency of horizontal vibration and the lower-frequencies of vertical vibration is less well known.

The effect of other characteristics of vibration on the discomfort of seated people have been investigated, in particular the effect of magnitude, duration, body supports, and direction; but their effect on the discomfort of standing people is unknown, and may be different, in particular because different mechanisms are involved when seated people and standing people are exposed to vibration. In particular, postural stability is expected to be an important cause of discomfort for standing people, but not for seated people.

Discomfort cannot be predicted by simple physical parameters such as acceleration, and can not always be predicted from the biodynamic response of the body. So, because of the subjective nature of discomfort, investigation must be conducted with subjective methods, where subjects describe the sensations they experience when they are exposed to vibration stimuli. A variety of methods can be used for this purpose.

So, this literature review has identified areas where further research is required. For predicting the discomfort caused by vertical vibration, it is necessary to understand the relations between the characteristics of vibration and the discomfort experienced by standing people. In particular, subjective experiments are needed to determine the effect of frequency on the discomfort of standing people exposed to horizontal and low-frequency (<3 Hz) vertical vibration, and the magnitude-dependence of this frequency effect. Additionally, the effects of postural supports and of the direction, waveform and duration of vibration on discomfort of standing people are unknown and may not be extrapolated from knowledge of the discomfort of seated people. Therefore, these factors need to be investigated in experimental studies. Experimental studies should be designed so that they bring answers to these questions, but also provide a better understanding of the mechanisms of vibration discomfort of standing people, so that the result can be interpreted in appropriate ways.

# Chapter 3

# Methods

## 3.1 Introduction

In this Chapter, the methods used for the research presented in this thesis are detailed, in particular the laboratory equipment and data processing techniques.

## 3.2 Apparatus

### 3.2.1 Vibrators

Three vibrators were used to generate motions. All vibrators were located in the Human Factors Research Unit of the Institute of Sound and Vibration Research, University of Southampton, Southampton, United Kingdom.

#### 3.2.1.1 Distortion

Signal distortion was measured for all vibrators. At each frequency of interest, and at typical magnitudes used in the experiments, sinusoidal signals were generated and the acceleration in the direction of the motion was recorded. The signals were recorded at sampling rates of 1000 Hz with the Tiab control system (Section 3.2.1.2) and 256 Hz on the Pulsar control systems. A preliminary test showed that the distortion was not affected by the presence of a subject on the table of the simulator, so the distortion were measured without subjects.

In order to take account of the subjective effect of frequency, the signals were then frequency-weighted. Based on the results of Chapter 4, the horizontal acceleration measured on the table of the vibrator was frequency-weighted using a weighting corresponding to constant velocity at frequencies between 0.5 and 3.15 Hz and constant acceleration at frequencies greater than 3.15 Hz (Chapter 4, Section 4.4.2). The vertical acceleration of the vibrator table was frequency-weighted using the weighting curve $W_b$ advocated in standards.

The recorded motions were resampled at 128 Hz (except motions measured on the six-axis simulator, which were not resampled) and their power spectral density spectrum was calculated in the frequency band 0 to 64 Hz (or 0 to 128 Hz for the six-axis simulator). The distortion was calculated with Equation (3.1):

$$Distortion = \sqrt{\frac{E_{outside}}{E_{total}}} \tag{3.1}$$

where:

- $E_{outside}$ is the acceleration power outside a third-octave band centred on the frequency of the motion (Figure 3.2)
- $E_{total}$ is the acceleration power over the whole frequency range.

An example of waveform with distortion 9% is shown in Figure 3.1, and its PSD spectrum is shown in Figure 3.2.

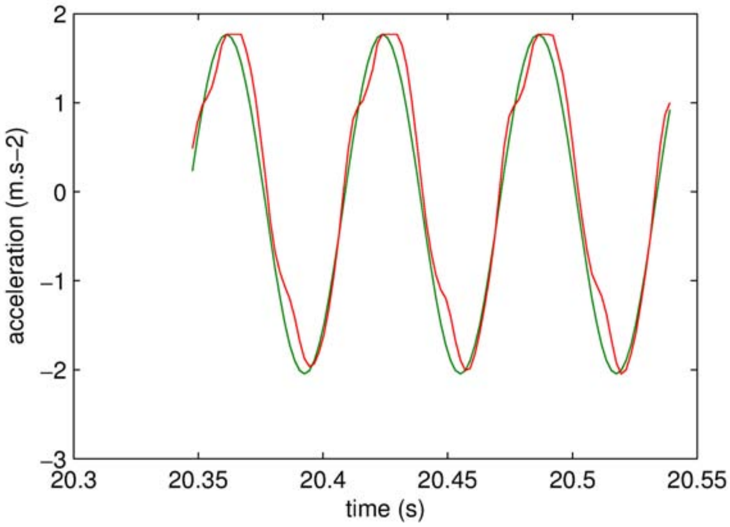


Figure 3.1: An example of vertical 4-Hz motion produced by the six-axis simulator (medium magnitude; see Tables 3.6 and 3.7). The distortion is 12 %.

#### 3.2.1.2 Horizontal motions

A hydraulic vibrator capable of horizontal displacements of 1-metre (peak-to-peak) was used when subjects were exposed to horizontal vibration. The vibrator table had dimensions 1500 mm x 1000 mm (Figures 3.4 and 3.3). For Experiments 1 and 3 (Chapters 4 and 6), the vibrator was controlled by a STI Tiab Digital Control System provided by Servo

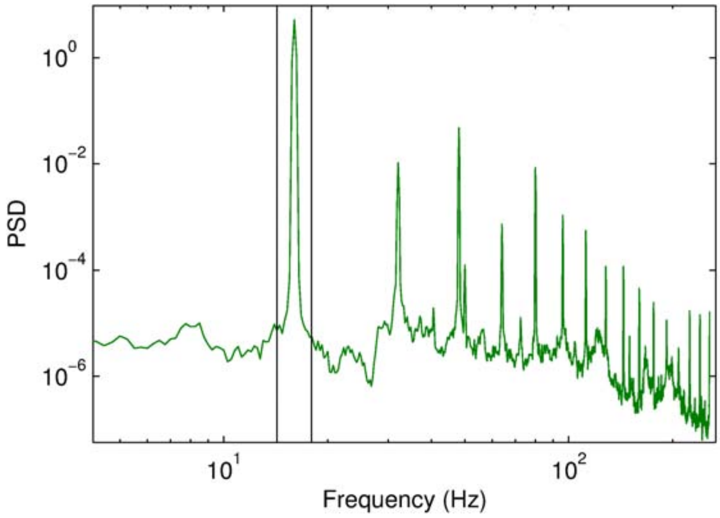


Figure 3.2: PSD spectrum of the motion shown in Figure 3.1, and octave-band used for the calculation of distortion. The distortion is 12 %.

Technique International. For Experiment 4 (Chapter 7), the vibrator was controlled by a Pulsar Digital Controller provided by Servotest Systems.

Distortion was measured with both control systems. Distortion was measured with the STI Tiab Digital Control System at each preferred third-octave frequency in the range 0.5 to 16 Hz, at magnitudes used in Experiment 1 (Chapter 4): the lowest, mid-range and greatest magnitudes used (see Table 3.1). The distortion values are reported in Table 3.2. Distortion was also measured with identical motions with the Pulsar Digital Controller, and the values are reported in Table 3.3.

Table 3.1: Magnitudes of horizontal motions used to measure distortion.

| Frequency (Hz) | Low magnitude ($m.s^{-2}$ r.m.s.) | Medium magnitude ($m.s^{-2}$ r.m.s.) | High magnitude ($m.s^{-2}$ r.m.s.) |
|---|---|---|---|
| 0.5 | 0.04 | 0.07 | 0.22 |
| 0.63 | 0.04 | 0.08 | 0.27 |
| 0.8 | 0.05 | 0.10 | 0.33 |
| 1 | 0.06 | 0.13 | 0.40 |
| 1.25 | 0.08 | 0.15 | 0.48 |
| 1.6 | 0.09 | 0.19 | 0.59 |
| 2 | 0.11 | 0.23 | 0.72 |
| 2.5 | 0.14 | 0.28 | 0.87 |
| 3.15 | 0.17 | 0.33 | 1.06 |
| 4 | 0.20 | 0.41 | 1.29 |
| 5 | 0.25 | 0.50 | 1.57 |
| 6.3 | 0.30 | 0.60 | 1.91 |
| 8 | 0.37 | 0.73 | 2.32 |
| 10 | 0.45 | 0.89 | 2.82 |
| 12.5 | 0.54 | 1.08 | 3.43 |
| 16 | 0.66 | 1.32 | 4.17 |

Table 3.2: Distortion measured with the horizontal vibrator and the STI Tiab control system (the low, medium and high magnitudes are defined in Table 3.1).

| | Unweighted distortion | | | Weighted distortion | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | Low magnitude | Medium magnitude | High magnitude | Low magnitude | Medium magnitude | High magnitude |
| 0.5 | 62 % | 44 % | 29 % | 33 % | 21 % | 12 % |
| 0.63 | 51 % | 34 % | 24 % | 28 % | 19 % | 10 % |
| 0.8 | 43 % | 34 % | 22 % | 24 % | 20 % | 12 % |
| 1 | 25 % | 23 % | 16 % | 15 % | 13 % | 8 % |
| 1.25 | 14 % | 16 % | 11 % | 9 % | 9 % | 6 % |
| 1.6 | 12 % | 12 % | 10 % | 7 % | 7 % | 5 % |
| 2 | 10 % | 9 % | 7 % | 7 % | 5 % | 4 % |
| 2.5 | 8 % | 7 % | 6 % | 4 % | 4 % | 4 % |
| 3.15 | 8 % | 7 % | 6 % | 4 % | 4 % | 5 % |
| 4 | 6 % | 6 % | 7 % | 4 % | 4 % | 5 % |
| 5 | 6 % | 5 % | 6 % | 3 % | 4 % | 5 % |
| 6.3 | 5 % | 6 % | 5 % | 3 % | 4 % | 4 % |
| 8 | 5 % | 4 % | 5 % | 4 % | 3 % | 4 % |
| 10 | 4 % | 5 % | 6 % | 3 % | 2 % | 5 % |
| 12.5 | 5 % | 4 % | 4 % | 3 % | 2 % | 3 % |
| 16 | 4 % | 3 % | 3 % | 2 % | 2 % | 2 % |

#### 3.2.1.3 Vertical motions

A hydraulic vibrator capable of 1-metre vertical displacement (peak-to-peak) was used when subjects were exposed to vertical vibration. The vibrator table had dimensions 1500 mm x 890 mm (Figures 3.5 and 3.6). For Experiment 1 (Chapter 4), the vibrator was controlled by an analogue control system. For Experiment 4 (Chapter 7), it was controlled by a Pulsar Digital Controller provided by Servotest Systems.

Distortion was measured with the Pulsar Digital Controller at each preferred third-octave frequency in the range 0.5 to 16 Hz, at magnitudes used in Experiment 1 (Chapter 4): the lowest, mid-range and greatest magnitude used, as shown in Table 3.4. The distortion values are reported in Table 3.5. Distortion was not measured with the analogue control system, but the motions recorded during the experiment show that the quality of the motions produced was comparable with that of the motions produced with the digital control system.

#### 3.2.1.4 Multi-axis motions

A hydraulic simulator capable of reproducing multi-axis motions including fore-and-aft, lateral and vertical translation, roll, pitch and yaw, was used for the Experiment 4 and 5 (Figure 3.7). The maximum stroke is 500 mm in the fore-and-aft and lateral directions,

Table 3.3: Distortion measured with the horizontal vibrator and the Servotest Pulsar control system (the values for low, medium and high magnitude are reported in Table 3.1).

| | Unweighted distortion | | | Weighted distortion | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | Low magnitude | Medium magnitude | High magnitude | Low magnitude | Medium magnitude | High magnitude |
| 0.5 | 39 % | 21 % | 9 % | 19 % | 9 % | 3 % |
| 0.63 | 31 % | 19 % | 9 % | 11 % | 7 % | 4 % |
| 0.8 | 37 % | 21 % | 9 % | 14 % | 8 % | 4 % |
| 1 | 33 % | 17 % | 10 % | 13 % | 7 % | 5 % |
| 1.25 | 30 % | 16 % | 10 % | 13 % | 7 % | 6 % |
| 1.6 | 22 % | 13 % | 10 % | 10 % | 7 % | 6 % |
| 2 | 21 % | 12 % | 10 % | 11 % | 7 % | 7 % |
| 2.5 | 18 % | 11 % | 11 % | 10 % | 7 % | 8 % |
| 3.15 | 18 % | 10 % | 11 % | 10 % | 8 % | 9 % |
| 4 | 12 % | 9 % | 11 % | 9 % | 7 % | 9 % |
| 5 | 11 % | 8 % | 9 % | 8 % | 7 % | 8 % |
| 6.3 | 11 % | 8 % | 7 % | 7 % | 6 % | 6 % |
| 8 | 7 % | 6 % | 4 % | 5 % | 4 % | 3 % |
| 10 | 9 % | 5 % | 2 % | 6 % | 3 % | 1 % |
| 12.5 | 14 % | 7 % | 2 % | 9 % | 4 % | 1 % |
| 16 | 4 % | 3 % | 2 % | 3 % | 2 % | 3 % |

1000 mm in the vertical direction, and ± 10 degrees in rotational axes. The simulator was controlled by a Pulsar Digital Controller provided by Servotest Systems.

Distortion was measured at 4 Hz, at magnitudes used in Experiment 2 (Chapter 5): the lowest, mid-range and greatest magnitudes used, as shown in Table 3.6. The distortion values are reported in Table 3.7.

The cross-axis coupling was also measured at 4 Hz for those magnitudes of motions. The cross-axis coupling was calculated as the ratio of the r.m.s. acceleration in non-desired directions to the r.m.s. acceleration in the desired direction of vibration. Accelerations were measured in the frequency range 0 to 128 Hz, with no frequency weightings or axis weightings used.

The desired motions were in the fore-and-aft, lateral, and vertical directions. Accelerations were measured in the three axes of translation (fore-and-aft, lateral and vertical) and the three axes of rotation (pitch, roll, and yaw).

At each magnitude of 4-Hz vibration (Table 3.6), the maximum cross-axis coupling between the expected direction of vibration and other translational directions, and the maximum cross-axis coupling between the expected direction of vibration and rotational axes are reported in Table 3.8.

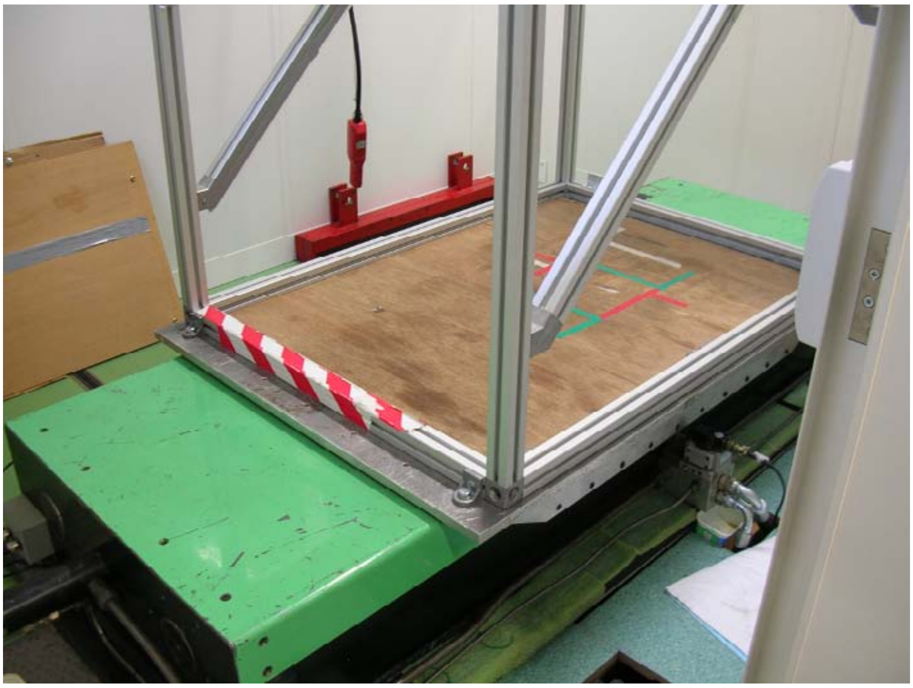


Figure 3.3: Photograph of the 1-metre horizontal vibrator.

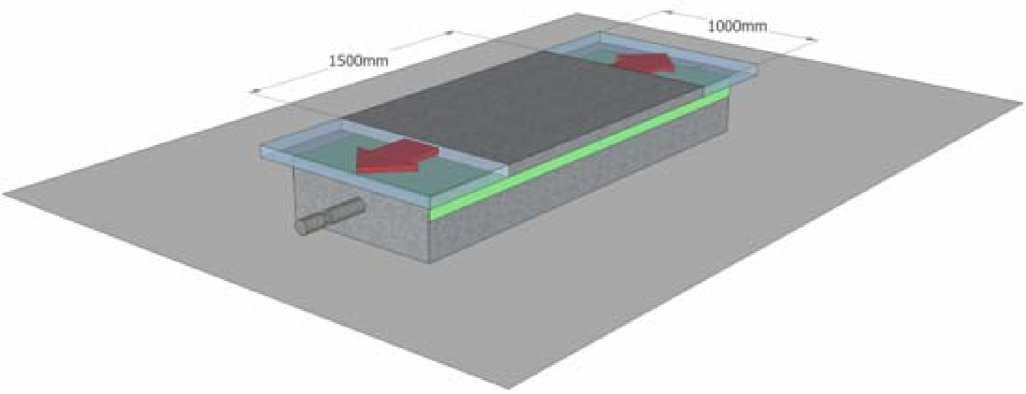


Figure 3.4: Model of the 1-metre horizontal vibrator. The translucent areas show the maximum displacement of the platform.

### 3.2.2 Vibration measurement

#### 3.2.2.1 Direction of measurement

In all experiments, accelerations were measured on the vibrator platform in the directions of the excitations. A basicentric coordinate system was used, as recommended in Section 5.2.1 of ISO 2631-1 (1997) and shown in Figure 3.8. In Experiment 3 (Chapter 6), the acceleration was also measured on the safety frame and the body supports in both horizontal directions in order to measure the in-axis and cross-axis response of the frame.

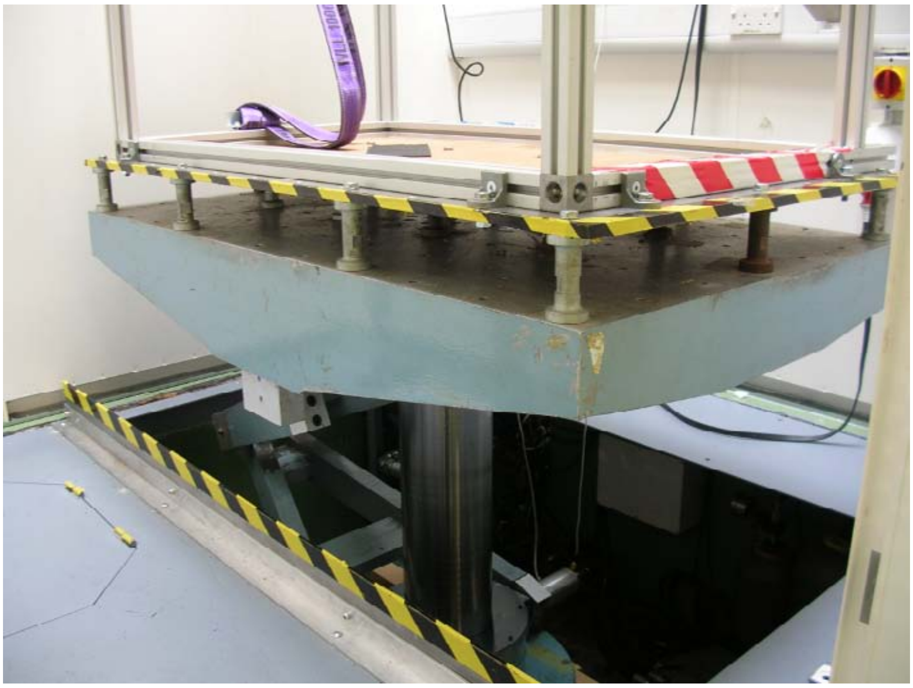


Figure 3.5: The 1-metre stroke vertical vibrator.

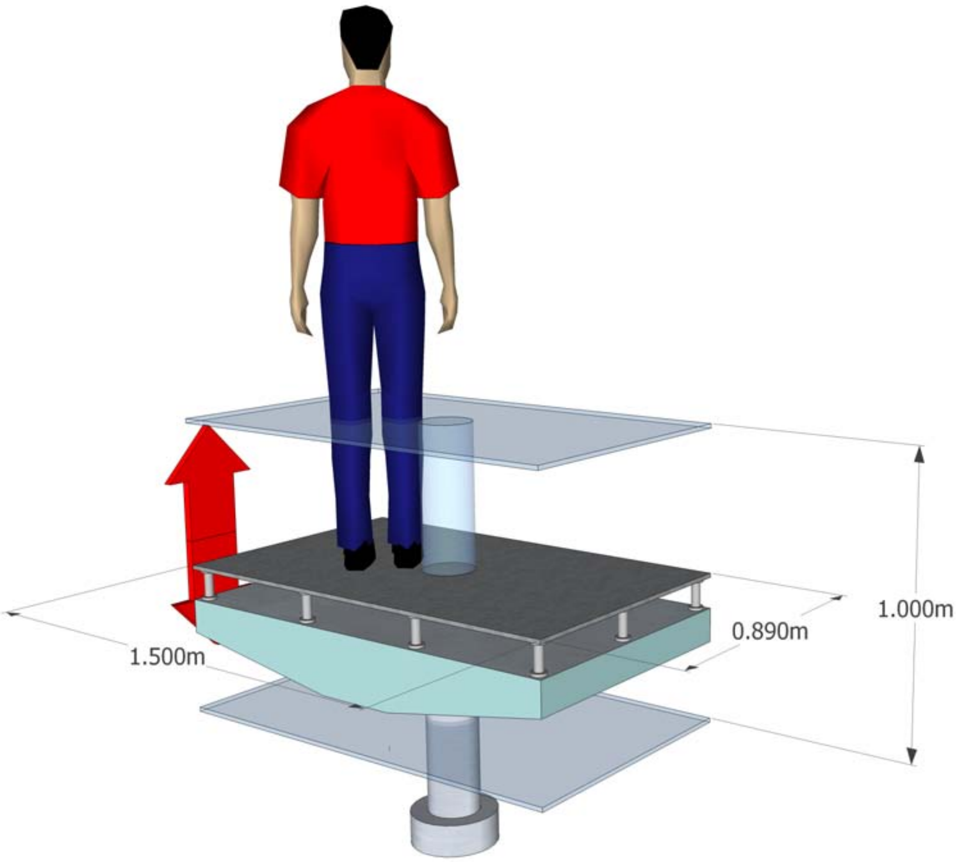


Figure 3.6: Model of the 1-metre vertical vibrator. The translucent areas show the maximum displacement of the platform.

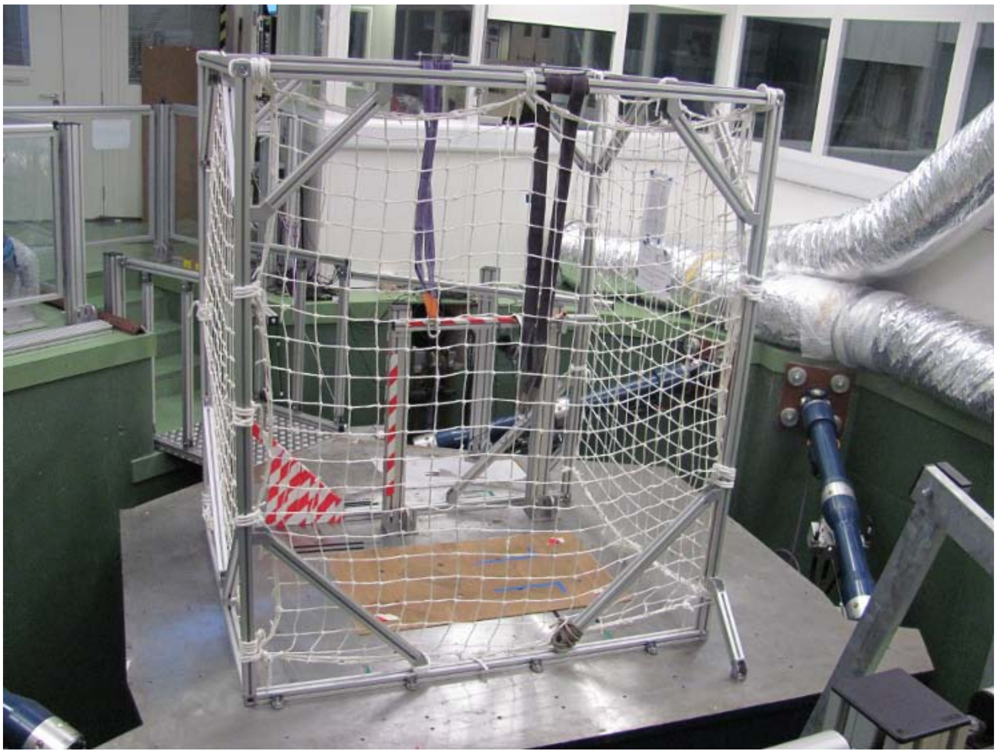


Figure 3.7: Six-axis simulator equipped with safety frame.

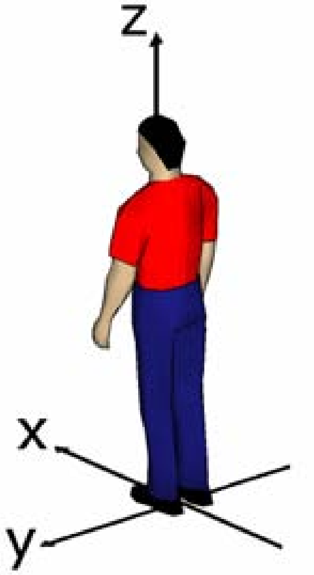


Figure 3.8: Basicentric axes of the human body as defined in ISO 2631-1 (1997).

Table 3.4: Magnitudes of vertical motions used to measure distortion.

| Frequency (Hz) | Low magnitude ($m.s^{-2}$ r.m.s.) | Medium magnitude ($m.s^{-2}$ r.m.s.) | High magnitude ($m.s^{-2}$ r.m.s.) |
|---|---|---|---|
| 0.5 | 0.11 | 0.28 | 0.7 |
| 0.63 | 0.14 | 0.35 | 0.89 |
| 0.8 | 0.18 | 0.44 | 1.12 |
| 1 | 0.22 | 0.56 | 1.41 |
| 1.25 | 0.22 | 0.56 | 1.41 |
| 1.6 | 0.22 | 0.56 | 1.41 |
| 2 | 0.22 | 0.56 | 1.41 |
| 2.5 | 0.22 | 0.56 | 1.41 |
| 3.15 | 0.22 | 0.56 | 1.41 |
| 4 | 0.22 | 0.56 | 1.41 |
| 5 | 0.22 | 0.56 | 1.41 |
| 6.3 | 0.22 | 0.56 | 1.41 |
| 8 | 0.22 | 0.56 | 1.41 |
| 10 | 0.22 | 0.56 | 1.41 |
| 12.5 | 0.22 | 0.56 | 1.41 |
| 16 | 0.22 | 0.56 | 1.41 |

#### 3.2.2.2 Transducers and signal conditioning

In experiments involving single-axis vibration (Experiments 1, 3 and 4; Chapters 4, 6 and 7) the vibration was measured using piezoresistive accelerometers of type Entran EGCSY-240D*-10. In experiments involving multi-axis vibration (Experiments 2 and 5; Chapters 5 and 8), the acceleration was measured by Setra 141A capacitive accelerometers secured to the table of the simulator. In Experiment 4 (Chapter 7), the signals from the transducers were amplified using FYLDE FE-366-TA dual channel amplifiers. Transducers were calibrated using the gravity acceleration ($\pm g$) and had a DC response.

#### 3.2.2.3 Signal generation and data acquisition

In Experiments 1 and 3 (Chapters 4 and 6), the vibration signals were generated and acquired using HVLab (version 3.81) software. They were generated and acquired at 1000 samples/second and low-pass filtered at 40 Hz. In Experiments 2, 4 and 5 (Chapters 5, 7 and 8), the vibration signals were generated and acquired in Pulsar (version 1.4) software, provided by Servotest Testing Systems. The signals were generated and acquired at 256 samples/second and low-pass filtered at 64 Hz.

Table 3.5: Distortion measured with the vertical vibrator and the Servotest Pulsar control system (the low, medium and high magnitude are defined in Table 3.4).

| | Unweighted distortion | | | Weighted distortion | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | Low magnitude | Medium magnitude | High magnitude | Low magnitude | Medium magnitude | High magnitude |
| 0.5 | 12 % | 6 % | 4 % | 19 % | 9 % | 6 % |
| 0.63 | 7 % | 4 % | 4 % | 11 % | 6 % | 5 % |
| 0.8 | 5 % | 3 % | 3 % | 7 % | 4 % | 4 % |
| 1 | 3 % | 1 % | 3 % | 4 % | 2 % | 4 % |
| 1.25 | 2 % | 1 % | 2 % | 4 % | 2 % | 3 % |
| 1.6 | 3 % | 2 % | 2 % | 6 % | 3 % | 3 % |
| 2 | 4 % | 1 % | 1 % | 7 % | 2 % | 2 % |
| 2.5 | 5 % | 1 % | 1 % | 9 % | 2 % | 2 % |
| 3.15 | 6 % | 2 % | 2 % | 7 % | 2 % | 2 % |
| 4 | 6 % | 1 % | 1 % | 4 % | 1 % | 1 % |
| 5 | 5 % | 2 % | 1 % | 3 % | 1 % | 0 % |
| 6.3 | 6 % | 3 % | 1 % | 3 % | 2 % | 1 % |
| 8 | 5 % | 3 % | 1 % | 2 % | 2 % | 1 % |
| 10 | 6 % | 2 % | 1 % | 3 % | 1 % | 1 % |
| 12.5 | 7 % | 3 % | 1 % | 3 % | 2 % | 1 % |
| 16 | 6 % | 2 % | 1 % | 2 % | 1 % | 1 % |

Table 3.6: Magnitudes of the 4-Hz motions used to measure distortion on the six-axis simulator.

| | Low magnitude ($m.s^{-2}$ r.m.s.) | Medium magnitude ($m.s^{-2}$ r.m.s.) | High magnitude ($m.s^{-2}$ r.m.s.) |
|---|---|---|---|
| Fore-and-aft | 0.15 | 0.23 | 0.29 |
| Lateral | 0.29 | 0.46 | 0.58 |
| Vertical | 0.58 | 0.92 | 1.15 |

## 3.3 Test conditions

### 3.3.1 Vibration

In all experiments, subjects were exposed to vibration. All experiments were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research, University of Southampton. All subjects were volunteers and could quit the experiment at any time without providing a reason. For each experiment, subjects were provided an instruction sheet. Copies of these instruction sheets are included in the Appendices.

Table 3.7: Distortion measured with the six-axis simulator. The frequency of the signal was 4 Hz and the values for low, medium and high magnitude are reported in Table 3.6.

| | Direction of excitation | Low Magnitude | Medium Magnitude | High magnitude |
|---|---|---|---|---|
| Unweighted | Fore-and-aft | 11 % | 10 % | 5 % |
| | Lateral | 14 % | 6 % | 5 % |
| | Vertical | 16 % | 10 % | 8 % |
| Weighted | Fore-and-aft | 8 % | 7 % | 3 % |
| | Lateral | 11 % | 4 % | 4 % |
| | Vertical | 14 % | 9 % | 7 % |

Table 3.8: Maximum cross-axis coupling on the six-axis simulator. The frequency of the signal was 4 Hz and the values for low, medium and high magnitude are reported in Table 3.6.

| | Direction of excitation | Low Magnitude | Medium Magnitude | High magnitude |
|---|---|---|---|---|
| Coupling with translational axes | Fore-and-aft | 10 % | 6 % | 3 % |
| | Lateral | 5 % | 4 % | 4 % |
| | Vertical | 5 % | 4 % | 2 % |
| Coupling with rotational axes | Fore-and-aft | 0.02 rad/m | 0.01 rad/m | 0.01 rad/m |
| | Lateral | 0.03 rad/m | 0.02 rad/m | 0.01 rad/m |
| | Vertical | 0.09 rad/m | 0.08 rad/m | 0.03 rad/m |

### 3.3.2 Safety frame

In all experiments, the subjects stood on a wooden board secured to the table of the vibrator and within an aluminium frame. The frame used is shown in Figure 3.9 for the horizontal and vertical simulators and in Figure 3.10 for the six-axis simulator. The frame mounted on the horizontal vibrator had dimensions 975 mm x 1270 mm x 2000 mm (length x width x height). The frame mounted on the vertical vibrator had dimensions 670 mm x 1270 mm x 2000 mm. The frame mounted on the six-axis simulator had dimensions 1900 mm x 1460 mm x 2100 mm. The subjects wore a loose harness secured to the frame in case they should fall. The harness did not provide support or restrict movement when subjects stood as instructed (Figure 3.11). Wooden boards were also mounted on the frame for safety, to be used as supports in Experiment 3 (Chapter 6), and to close the visual field of subjects in Experiment 1 (Chapter 4).

### 3.3.3 Visual field

The visual conditions varied between Experiments. In Experiment 3 (Chapter 6), the subjects could see outside the frame mounted on the vibrator. Part of their visual field was

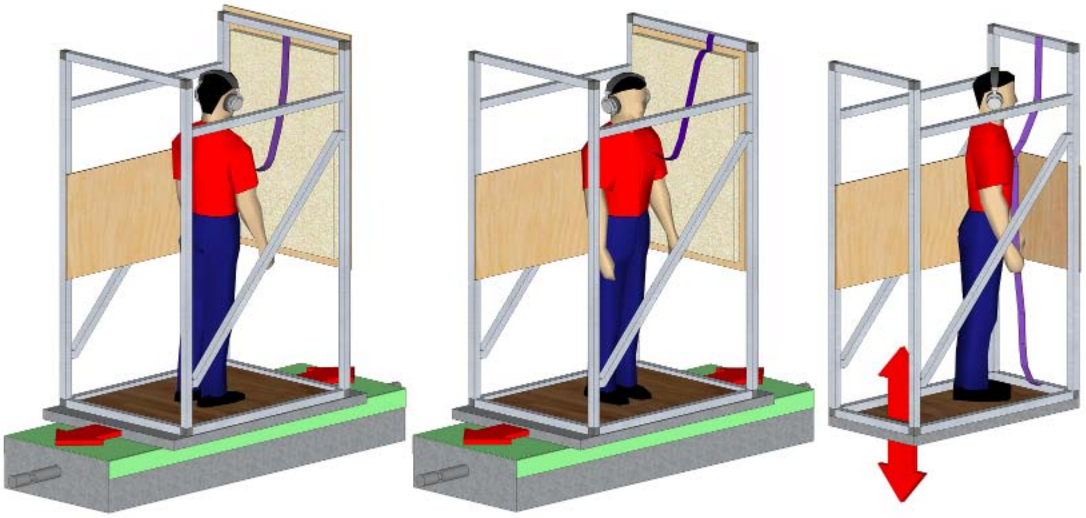


Figure 3.9: Experimental setup with the aluminium frame mounted on the horizontal and vertical vibrators (Experiment 4; Chapter 7).

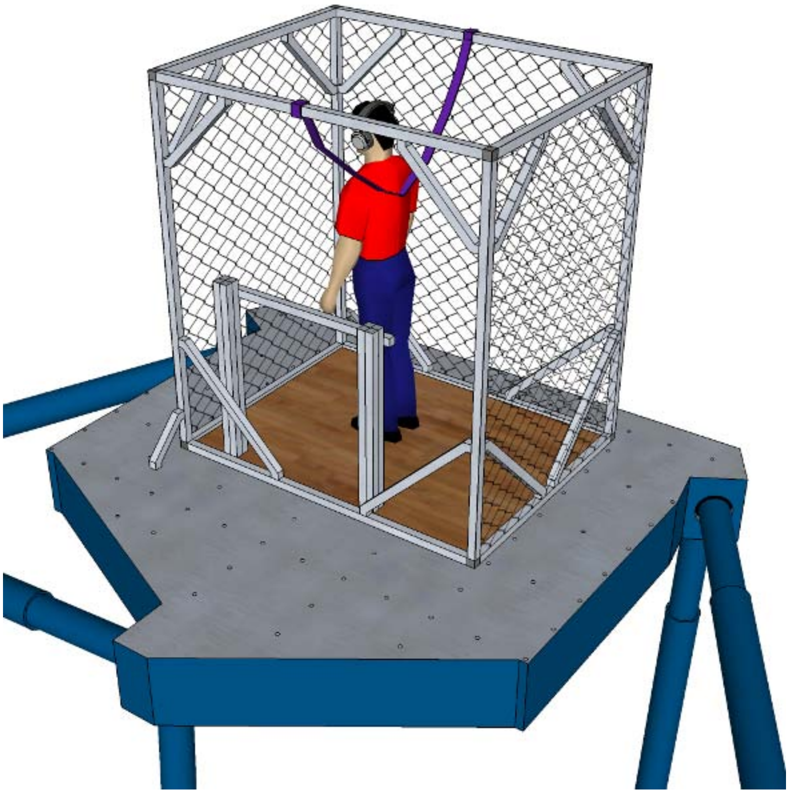


Figure 3.10: Aluminium frame mounted on the six-axis simulator.

Figure 3.11: Harness system used on the singe-axis vibrators (horizontal and vertical).

fixed, and part of their visual field was mobile (Figure 3.12.a). In Experiment 1 (Chapter 4), the cabin was closed so that the whole visual field of the subjects was moving (Figure 3.12.b). In Experiments 4, 2 and 5 (Chapters 5, 7 and 8), the subjects were required to close their eyes during the vibration.

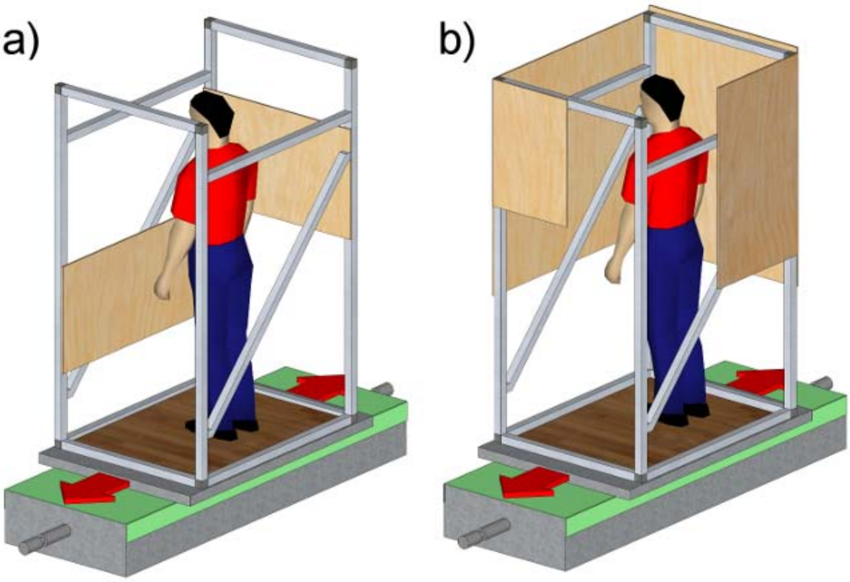


Figure 3.12: Different visual field conditions used in the experiments: a) Open visual field (Chapter 6) b) Closed visual field (Chapter 4).

### 3.3.4 Acoustic conditions

When the motion simulators were generating motions, they produced acoustical noise. The level of the noise generated by the horizontal and the vertical simulators was less than 57 dB(A) at the location of the subjects. The ambient noise occasionally reached 60 dB(A) on the vertical vibrator when a pump was running, but this event was not correlated with the vibration and hence was not expected to bias the subjective comparisons. When the six-axis simulator was running, the noise level at the location of the subject was less than 51 dB(A).

In order to mask the background noise and create an acoustical environment independent of the vibration stimulus, white noise created by a calibrated generator was presented to the subjects through calibrated headphones in all experiments. The sound pressure level of the white noise was 65 dB(A).

In all experiments, the experimenter communicated with the subjects with a microphone connected to the headphones.

## 3.4 Psychophysical methods

### 3.4.1 Magnitude estimation

In all experiments, the method of magnitude estimation with a reference was used. This method was initiated by Stevens (1975) and used by Morioka and Griffin (2006a, 2006b) and Wyllie and Griffin (2007, 2009). The purpose of the method is to measure the perceived intensity (or subjective magnitude) of a series of physical stimuli (the ”test” stimuli), which can be for example vibration, sound, or light. When magnitude estimation is used, subjects are exposed to the stimuli and asked to provide a number reflecting its magnitude (e.g., the size of a shape, the brightness of a light stimulus, the loudness of a sound, or the discomfort caused by a vibration). A reference stimulus can be used. If it is the case, the reference stimulus, which is identical throughout an experiment, is presented before each test stimuli, and the subjects are asked to estimate the magnitude of the test stimuli in comparison with the reference stimulus (generally, assuming the magnitude of the reference is 100). The reference should be chosen so that its magnitude is approximately in the middle of the range of magnitudes of the test stimuli (Stevens, 1975). However, Stevens (1975) found that a good consistency was achieved when no reference was used and the subjects were asked to give any value they felt appropriate to estimate the magnitude of stimuli.

### 3.4.2 Stevens' power law

In Experiments 1, 2, 3 and 4 (Chapters 4, 5, 6 and 7), Stevens' power law was used to relate the magnitude of the sensation, $\psi$, induced by a motion to the physical magnitude, $\varphi$ of the motion (Stevens, 1956):

$$\psi = k\varphi^n \tag{3.2}$$

where $k$ (the "constant" in Stevens' power law) and $n$ (the "exponent") are assumed to be constant for a given stimulus. In the present case, $\varphi$ is the magnitude of the vibration, and $\psi$ is the subjective magnitude felt and reported by the subjects.

Equation (3.2) can be written in logarithmic form:

$$\log(\psi) = \log(k) + n\log(\varphi) \tag{3.3}$$

By performing linear regression (Section 3.4.3) between the experimental values of $\log(\psi)$ and $\log(\varphi)$, estimates of the constant $k$ and the exponent $n$ were obtained for each subject, each frequency, each direction, and for each waveform. These parameters were then generally used to determine the physical magnitude $\varphi$ corresponding to a given subjective magnitude (i.e. discomfort level) $\psi_1$, using Equation (3.4):

$$\varphi = \left(\frac{\psi_1}{k}\right)^{1/n} \tag{3.4}$$

When the vibration magnitude is close to the perception threshold, an additional term is required in Equations (3.2) and (3.3) to take account of the perception threshold. Equation (3.3) becomes:

$$\log(\psi) = \log(k) + n\log(\varphi - \varphi_0) \tag{3.5}$$

where $\varphi_0$ is the acceleration perception threshold. If this equation is used to perform the regression and the threshold is not known, it is necessary to perform a 3-parameter non-linear regression. However, when the magnitude is not close to the perception threshold, the additional term can be neglected and linear regression can be performed, as in the present work. This choice is discussed in Chapter 9.

In all experiments, two possible approaches could have been used. In the first approach, linear regressions are performed with each individual set of data (bewteen 5 and 10 points), resulting of individual values of parameters, and individual equivalent comfort contours. In the second approach, linear regressions are performed on data pooled from all subjects, resulting in single values for the parameters. Although the second approach has the advantage of performing a linear regression with more points, the first approach was adopted, because it provides a representation of the sensitivity of each subjects (which can vary from one subject to another), and allowed more statistical analyses, in particular with the values of the parameters.

### 3.4.3 Robust regression

When linear regressions were performed between the physical magnitude $\log(\varphi)$ and the subjective magnitude $\log(\psi)$, a method of robust regression was used. This bisquare-weighted least squares method, detailed by Fox (2002), was designed to ignore outlier values when they are clearly inconsistent with the rest of the data. The method is based on weighted least squares: the general principle is that the parameters of the regression are obtained by minimizing the weighted sum of the squared residuals (the residual is the difference between the actual data points and the predictions of the linear model). Initially, all data points receive an equal weight, and after a first regression has been performed, new weights are attributed using a function giving less weight to points that are far off the regression line. Bisquare weights were used; their expression is shown in Equation (3.6) and the shape of the function is shown in Figure 3.13:

$$w_i = \begin{cases} \left[1 - \left(\frac{|e_i|}{k}\right)^2\right]^2 & , |e_i| < k \\ 0 & , |e_i| \geq k \end{cases} \tag{3.6}$$

where:

- $w_i$ is the weight given to the $i$-th data point for the next iteration
- $e_i$ is the residual from the $i$-th data point: $e_i = y_i - (a + b \cdot x_i)$
- $k$ is the cut-off parameter: $k = 6.9459E$
- $E$ is the median value of the residuals from all data points

Equation (3.6) implies that the cut-off parameter $k$ is proportional to the median residual. That means that the closer the bulk of data points will be to a straight line, the less tolerant to outliers the algorithm will be. Using the new weights, a regression is performed using the method of weighted least squares; so, a new set of parameters is obtained and the process is repeated until convergence of the regression parameters. An example is shown in Figure 3.14.

This method was chosen based on the hypothesis that if a point in the middle of the magnitude range is completely inconsistent with the general trend defined by all other

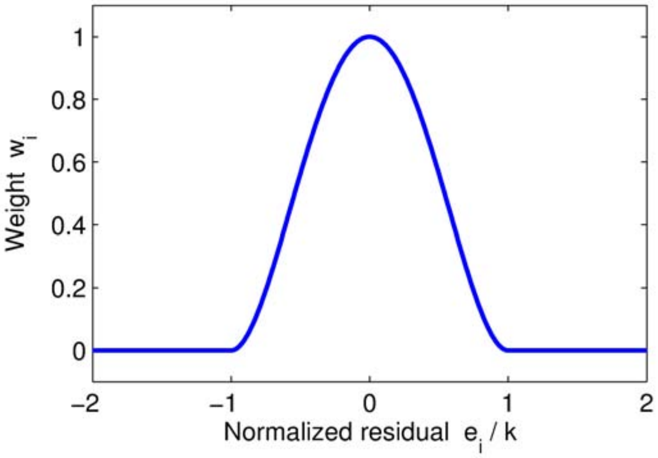


Figure 3.13: Function used for calculating the bisquare weights (Equation (3.6). The residual $e_i$ is the distance between the measured data and the prediction of the linear model, and the cut-off parameter is $k = 6.9459E$, where $E$ is the median residual.

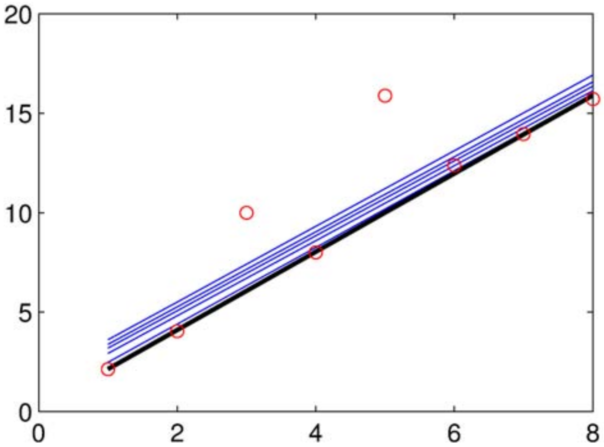


Figure 3.14: An example of robust regression where the weight associated with two outliers decreases progressively until they are completely discarded by the algorithm.

points (or most other points), then it is not the result of the effect being measured, but is rather a measurement error; it could be caused by the subject not paying attention and providing a random answer, or by a misunderstanding of the response. As such, it should not be taken into account. The method of bisquare-weighted least square regression is a way of achieving this, as shown in Figure 3.14 with an example. It was implemented in a Matlab script which is included in the Appendix.

### 3.4.4 Constant stimulus

A variant of the method of constant stimulus was used in a preliminary study to Experiment 4 (Chapter 7). The purpose of the method was to determine at which magnitude a test motion was equivalent in discomfort to a fixed reference motion stimulus. The motions were presented in pairs, with the first motions being the reference and the second being the test motion presented at a specific magnitude. The subjects were then asked which of the two motions was worst. When the test motion was presented at the lowest magnitudes, the reference was more uncomfortable than the test; when the test was presented at the highest magnitudes, it was worst than the reference. The magnitude at which the transition between these two zones happened was identified and retained as the 'equivalence magnitude'.

## 3.5 Data analysis

### 3.5.1 Data analysis software

Mathworks MATLAB software (version 7.5) was used to process the results. Scripts were written to perform linear regressions (Section 3.4.3), and to calculate equivalent comfort contours. The Matlab Toolbox "HVLab HRV" (version 1.1) developed by the Human Factors Research Unit (University of Southampton) was used for signal processing. SPSS Inc. version 14.0 and the Matlab statistics toolbox were used to perform statistical analysis on the data (see Section 3.5.2). Piface (Version 1.72) software was used for statistical power calculations.

### 3.5.2 Statistical tests

To avoid making hypotheses on the distribution of data, non-parametrical statistical tests were used. The tests used for each experimental situation are shown in Table 3.9.

Table 3.9: Non-parametrical statistical tests used in this research.

| **Case** | **Statistical test used** |
|---|---|
| 2 related samples | Wilcoxon signed ranks test |
| $k$ related samples | Friedman two-way analysis of variance |
| 2 independent samples | Wilcoxon-Mann-Whitney test |
| $k$ independent samples | Kruskal-Wallis one-way analysis of variance |
| Correlation between two variables | Spearman rank-order correlation coefficient |
| 2 related samples, binary variable | McNemar change test |
| $k$ related samples, binary variable | Cochran $Q$ test |

# Chapter 4

# The effect of frequency on the vibration discomfort of standing people

## 4.1 Introduction

Due to the complexity of mechanisms involved in vibration discomfort, the sensitivity of people to vibration depends on the frequency of vibration. When evaluating the subjective effects of vibration, it is therefore essential to take into account the difference in sensitivity to various frequencies of vibration, which is usually achieved through the use of equivalent sensation contours or frequency weightings. The experiment reported in this chapter was designed to investigate this effect.

Methods are advocated in British Standard 6841 (1987), European prestandard ENV 12299 (1999) and International Standard 2631 (1997) for evaluating vibration with respect to the discomfort of standing people. To reflect the assumed frequency-dependence of discomfort, the standards employ frequency weightings, but the dearth of relevant experimental studies resulted in the use of weightings for standing people derived from equivalent-sensation contours obtained with seated subjects. It is reasonable to suppose that there will be some differences between seated and standing people, and that the weightings for seated people may not be ideal for predicting the discomfort of standing people.

Various methods can be used to construct equivalent comfort contours, including magnitude production and magnitude estimation. For the vertical vibration of standing people, equivalent comfort contours have been constructed from experimental studies employing a variety of experimental methods over various frequency ranges: magnitude production with a semantic scale, 1-27 Hz (Chaney, 1965); magnitude production using a reference motion, 4-80 Hz (Jones and Saunders, 1972); method of adjustment with a random reference motion, 0.7-20 Hz (Ashley, 1970); magnitude estimation using numbers without a reference motion, 3-80 Hz (Oborne and Clarke, 1974); magnitude production using a reference motion, 0.5-300 Hz (Miwa, 1967b). Using a similar method and frequency range, Miwa (1967b) also constructed equivalent comfort contours for standing people exposed to horizontal vibration. Some of the above methods have been found to lack consistency, most notably methods relying on semantic labels where the interpretation can be highly dependent on the subject. The distortion of the motions used in previous studies was often unreported, but sometimes high. A more accurate reproduction of motion is now possible, the methods have been improved, and equivalent comfort contours can be determined for both vertical and horizontal vibration at the lower frequencies seldom investigated previously. There are significant motions in transport at low frequencies (ISO 2631-4, 2001), and increased understanding of the relative discomfort caused by low and high frequencies has important practical applications.

To understand the discomfort caused by vibration it is necessary to know the causes of discomfort. Landström and Lundström (1986) found that over the frequency range 2 to 16 Hz, the localization of discomfort and the type of sensation (e.g. trembling, swinging) caused by the vertical excitation of standing people depended on the frequency of vibration. A variation in response with the frequency of vibration may also be expected with horizontal excitation, especially because loss of balance may be produced by low frequency motions but not high frequency motions. With subjects exposed to narrow-band random motions of the same r.m.s. velocity in either the fore-and-aft or lateral direction at frequencies in the range 0.125 to 2 Hz, all subjective and objective indicators of loss of balance (displacement of the centre of pressure, loss of balance, and estimates of the probability of losing balance) peaked around 0.5 Hz (Nawayseh and Griffin, 2006).

The study reported in this chapter was designed to improve understanding of the discomfort of standing people exposed to vibration of the floor and determine how their discomfort depends on the frequency of fore-and-aft, lateral, and vertical excitation. It was hypothesized that, with each direction of excitation, both the sensitivity to vibration acceleration and the cause of discomfort would depend on the frequency of the vibration. The purpose was also to determine the localization of discomfort in the body, and to provide frequency weightings that can be practically used for evaluation vibration discomfort of standing people.

This study has been partly published (Thuong and Griffin, 2011b).

## 4.2 Method

### 4.2.1 Motions

All vibration stimuli used in the study were sinusoidal and 6 seconds in duration, including a 1-second cosine-tapered start and a 1-second cosine-tapered end. Subjects were exposed to pairs of motions: a 'reference vibration' followed by a 'test vibration' in the same direction (i.e. either fore and aft, lateral, or vertical).

The reference motion was a 2.5-Hz vibration with magnitude 0.35 m.s$^{-2}$ r.m.s.(for horizontal vibration) or 0.56 m.s$^{-2}$ r.m.s.(for vertical vibration).

With all three directions of motion, the 'test stimuli' were presented at the sixteen preferred one-third octave centre frequencies between 0.5 and 16 Hz (Table 4.1). At each frequency, the test stimuli were presented at nine magnitudes, in steps of 2 dB (Figure 4.1, Tables 4.1 and 4.2). The magnitudes of the stimuli were chosen in the expectation that they would cause approximately similar discomfort at each frequency, based on the results of preliminary studies.

The fidelity of the simulators, indicated by the ratio of the measured magnitudes to the desired magnitudes, is reported in Tables 4.3 and 4.4.

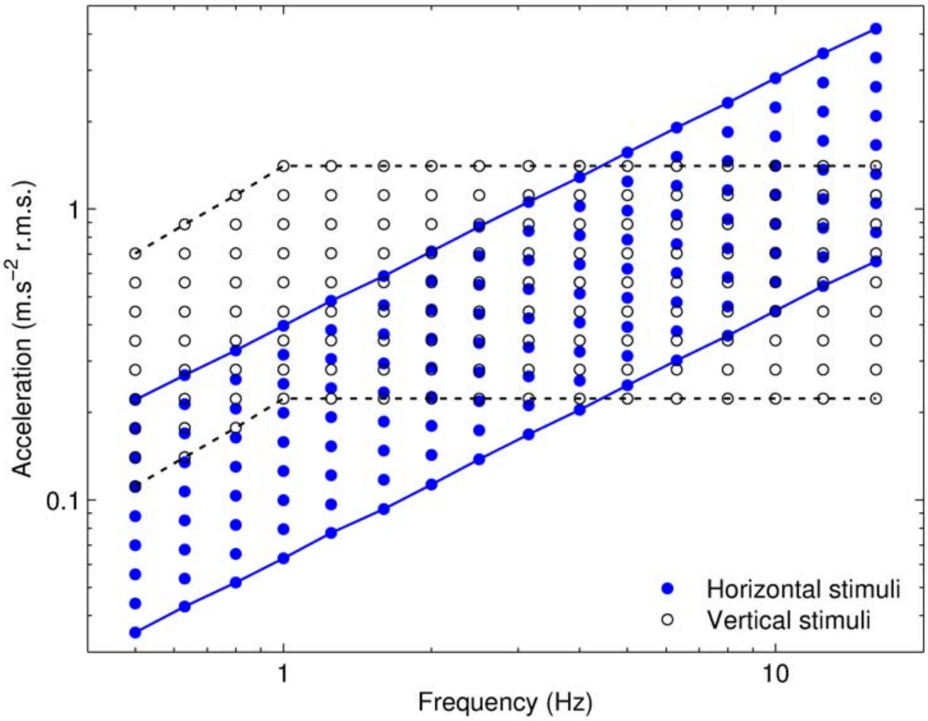


Figure 4.1: Frequencies and magnitudes of the vibration stimuli used in the experiment.

Table 4.1: Frequencies and magnitudes of the horizontal vibration stimuli used in the experiment.

| Frequency (Hz) | Magnitudes (m.s$^{-2}$ r.m.s.) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.04 | 0.04 | 0.06 | 0.07 | 0.09 | 0.11 | 0.14 | 0.18 | 0.22 |
| 0.63 | 0.04 | 0.05 | 0.07 | 0.08 | 0.11 | 0.13 | 0.17 | 0.21 | 0.27 |
| 0.8 | 0.05 | 0.07 | 0.08 | 0.10 | 0.13 | 0.16 | 0.21 | 0.26 | 0.33 |
| 1 | 0.06 | 0.08 | 0.1 | 0.13 | 0.16 | 0.2 | 0.25 | 0.32 | 0.40 |
| 1.25 | 0.08 | 0.1 | 0.12 | 0.15 | 0.19 | 0.24 | 0.31 | 0.38 | 0.48 |
| 1.6 | 0.09 | 0.12 | 0.15 | 0.19 | 0.23 | 0.29 | 0.37 | 0.47 | 0.59 |
| 2 | 0.11 | 0.14 | 0.18 | 0.23 | 0.28 | 0.36 | 0.45 | 0.57 | 0.72 |
| 2.5 | 0.14 | 0.17 | 0.22 | 0.28 | 0.35 | 0.44 | 0.55 | 0.69 | 0.87 |
| 3.15 | 0.17 | 0.21 | 0.27 | 0.33 | 0.42 | 0.53 | 0.67 | 0.84 | 1.06 |
| 4 | 0.20 | 0.26 | 0.32 | 0.41 | 0.51 | 0.65 | 0.81 | 1.02 | 1.29 |
| 5 | 0.25 | 0.31 | 0.39 | 0.50 | 0.62 | 0.79 | 0.99 | 1.24 | 1.57 |
| 6.3 | 0.30 | 0.38 | 0.48 | 0.60 | 0.76 | 0.96 | 1.20 | 1.51 | 1.91 |
| 8 | 0.37 | 0.46 | 0.58 | 0.73 | 0.92 | 1.16 | 1.46 | 1.84 | 2.32 |
| 10 | 0.45 | 0.56 | 0.71 | 0.89 | 1.12 | 1.41 | 1.78 | 2.24 | 2.82 |
| 12.5 | 0.54 | 0.68 | 0.86 | 1.08 | 1.37 | 1.72 | 2.16 | 2.72 | 3.43 |
| 16 | 0.66 | 0.83 | 1.05 | 1.32 | 1.66 | 2.09 | 2.63 | 3.31 | 4.17 |

### 4.2.2 Equipment

The motions were produced using two hydraulic vibrators capable of 1-metre displacement, one in the horizontal direction, and the other in the vertical direction. Fore-and-aft or lateral vibration was obtained by orientating subjects relative to the axis of motion (Figure 4.2). The simulators and their performances are described in Chapter 3, Section 3.2.1.

The motion stimuli were generated using HVLab software (version 3.81) with a sampling rate of 1000 samples per second. The acceleration of the platform was monitored using piezoresistive accelerometers (Entran Model EGCSY-240D*-10) and an HVLab data acquisition system. The acceleration was sampled at 1000 samples per second, after low-pass filtering at 40 Hz.

### 4.2.3 Subjects

Sixteen healthy male university students and staff with median age 25 years (range 20 to 29 y), stature 179 cm (164 to 193 cm), weight 77 kg (48 to 133 kg) participated in the studies with horizontal vibration. They attended two sessions, one for each direction of motion (i.e. fore-and-aft and lateral), each lasting approximately 60 minutes.

Sixteen healthy male university students and staff with median age 25 years (range 20 to 29 y), stature 176 cm (164 to 187 cm), weight 73 kg (48 to 92 kg) participated in the

Table 4.2: Frequencies and magnitudes of the vertical vibration stimuli used in the experiment.

| Frequency (Hz) | Magnitudes ($m.s^{-2}$ r.m.s.) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.11 | 0.14 | 0.18 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 |
| 0.63 | 0.14 | 0.18 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 |
| 0.8 | 0.18 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 |
| 1 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 1.25 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 1.6 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 2 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 2.5 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 3.15 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 4 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 5 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 6.3 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 8 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 10 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 12.5 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |
| 16 | 0.22 | 0.28 | 0.35 | 0.44 | 0.56 | 0.7 | 0.89 | 1.12 | 1.41 |

study using vertical vibration, including 10 subjects who participated in the studies with horizontal vibration. They attended one session lasting 60 minutes.

The physical characteristics of the subjects used in both studies are reported in Tables 4.5 and 4.6.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

### 4.2.4 Conditions and posture

The subjects wore socks but not shoes and wore a loose harness in case they should fall. The harness did not provide support or restrict movement when subjects stood as instructed. It was attached to an extruded aluminium frame secured to the 120 cm by 90 cm table of the vibrator. Wooden boards were attached to the aluminium frame, so that the visual field was closed and moved with the subjects who could not see outside the moving cabin (Figure 4.2).

The subjects maintained an upright posture, with their knees locked, and looked straight ahead. Their feet were parallel and separated so that their lateral 'base of support' (distance between the outer edges of their feet) was 350 mm, the median shoulder width for adult males (Pheasant, 1988).

The subjects wore headphones delivering broadband noise at 65 dB(A).

Table 4.3: Distribution of the ratio of the measured magnitude to the desired magnitude, at each frequency of horizontal vibration.

| Frequency (Hz) | Minimum | 25th percentile | 75th percentile | Maximum |
|---|---|---|---|---|
| 0.5 | 0.78 | 0.98 | 1.04 | 1.22 |
| 0.63 | 0.83 | 0.99 | 1.06 | 1.38 |
| 0.8 | 0.88 | 0.98 | 1.03 | 1.15 |
| 1 | 0.75 | 0.97 | 1.02 | 1.27 |
| 1.25 | 0.81 | 0.97 | 1.04 | 1.12 |
| 1.6 | 0.81 | 0.98 | 1.04 | 1.17 |
| 2 | 0.84 | 0.97 | 1.05 | 1.16 |
| 2.5 | 0.83 | 0.98 | 1.05 | 1.12 |
| 3.15 | 0.77 | 1.00 | 1.06 | 1.37 |
| 4 | 0.76 | 0.99 | 1.05 | 1.40 |
| 5 | 0.74 | 1.01 | 1.06 | 1.23 |
| 6.3 | 0.73 | 1.01 | 1.07 | 1.18 |
| 8 | 0.69 | 0.89 | 1.07 | 1.21 |
| 10 | 0.62 | 0.80 | 1.07 | 1.20 |
| 12.5 | 0.54 | 0.75 | 1.07 | 1.19 |
| 16 | 0.47 | 0.68 | 1.05 | 1.18 |

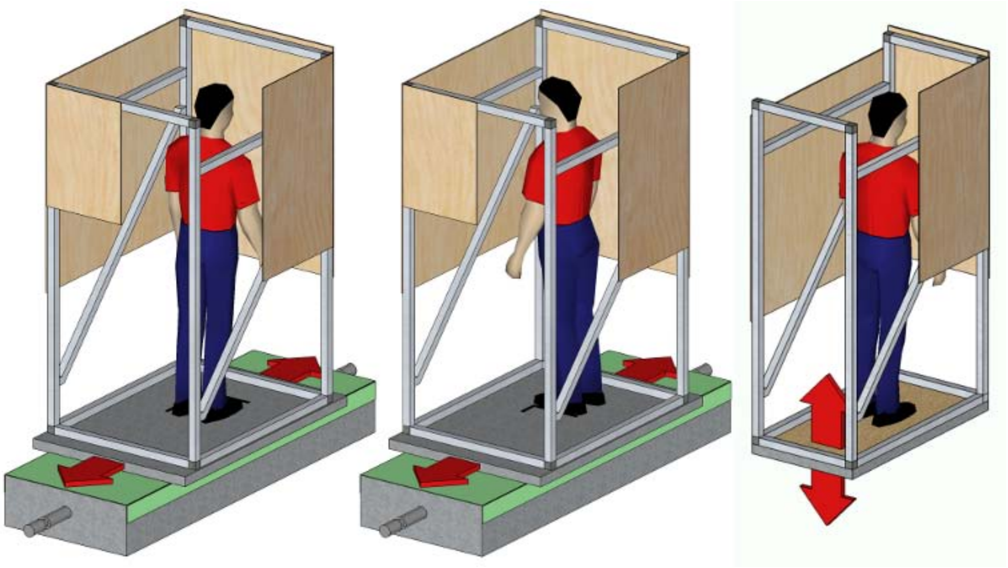


Figure 4.2: Models of the experimental setups used to expose subjects to fore-and-aft, lateral and vertical vibration respectively.

### 4.2.5 Procedure

The method of magnitude estimation was employed to determine the discomfort caused by each of the test motions relative to the discomfort caused by a reference motion presented in the same axis as the test motion.

Table 4.4: Distribution of the ratio of the measured magnitude to the desired magnitude, at each frequency of vertical vibration.

| Frequency (Hz) | Minimum | 25th percentile | 75th percentile | Maximum |
|---|---|---|---|---|
| 0.5 | 0.80 | 0.99 | 1.09 | 1.14 |
| 0.63 | 1.00 | 1.06 | 1.10 | 1.25 |
| 0.8 | 0.96 | 1.04 | 1.08 | 1.16 |
| 1 | 0.88 | 1.03 | 1.08 | 1.12 |
| 1.25 | 0.87 | 1.05 | 1.09 | 1.14 |
| 1.6 | 0.85 | 1.05 | 1.10 | 1.21 |
| 2 | 0.81 | 1.02 | 1.08 | 1.15 |
| 2.5 | 0.78 | 0.98 | 1.05 | 1.09 |
| 3.15 | 0.76 | 0.97 | 1.03 | 1.14 |
| 4 | 0.74 | 0.92 | 0.99 | 1.19 |
| 5 | 0.75 | 0.91 | 0.96 | 1.02 |
| 6.3 | 0.79 | 0.92 | 0.98 | 1.05 |
| 8 | 0.80 | 0.99 | 1.03 | 1.10 |
| 10 | 0.81 | 1.01 | 1.05 | 1.11 |
| 12.5 | 0.82 | 1.01 | 1.05 | 1.11 |
| 16 | 0.80 | 1.03 | 1.07 | 1.12 |

The subjects for the ‘horizontal’ experiment attended two sessions in which they were exposed to either fore-and-aft or lateral vibration: half of the subjects were first exposed to fore-and-aft vibration and half of the subjects began with lateral vibration. The subjects for the ‘vertical’ experiment attended one session.

Subjects were exposed to the reference motion (2.5 Hz at 0.35 $m.s^{-2}$ r.m.s. for horizontal vibration, 2.5 Hz at 0.56 $m.s^{-2}$ r.m.s. for vertical vibration), followed by a test motion at a randomly chosen frequency and magnitude from the range shown in Figure 4.1. After the presentation of the test motion, subjects were asked to provide a number reflecting the discomfort it caused, assuming the discomfort caused by the reference motion was 100. The subjects could ask for the pair of motions to be repeated if they were not sure of their judgement. Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli (Appendix A.1.1). This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli.

After the magnitude estimation of all stimuli, subjects were presented with additional vibration stimuli and asked to state where in the body they experienced most discomfort, or if discomfort arose due to postural instability (when exposed to horizontal vibration; Appendix A.1.2) or a different cause (when exposed to vertical vibration; Appendix A.1.3). If most discomfort arose from sensations in the body, they reported the location using the body map shown in Figure 4.3. These stimuli were identical to stimuli used in the first part

Table 4.5: Characteristics of the subjects who participated in the study with horizontal vibration. Subjects 1 to 10 also participated in the study with vertical vibration.

| Subject | Gender | Age | Height (cm) | Weight (kg) | Shoe size |
|---|---|---|---|---|---|
| 1 | M | 25 | 164 | 48 | 7.5 |
| 2 | M | 28 | 178 | 88 | 10 |
| 3 | M | 25 | 171 | 55 | 7.5 |
| 4 | M | 30 | 184 | 89 | 10.5 |
| 5 | M | 26 | 179 | 75 | 7 |
| 6 | M | 25 | 169 | 92 | 8.5 |
| 7 | M | 27 | 179 | 71 | 9 |
| 8 | M | 24 | 185 | 79 | 8.5 |
| 9 | M | 27 | 178 | 67 | 8 |
| 10 | M | 24 | 175 | 67 | 9 |
| 11 | M | 20 | 184 | 71 | 10.5 |
| 12 | M | 21 | 193 | 79 | 10 |
| 13 | M | 20 | 183 | 133 | 11.5 |
| 14 | M | 20 | 185 | 80 | 10.5 |
| 15 | M | 20 | 179 | 74 | 9 |
| 16 | M | 21 | 176 | 102 | 11.5 |

of the experiment (two stimuli at each frequency, at the third and seventh magnitudes in the ranges shown in Tables 4.1 and 4.2) and were presented in random order.

### 4.2.6 Analysis

Stevens' power law (Stevens, 1956) was used to relate the magnitude estimates of subject discomfort, $\psi$, to the physical magnitudes of the motions, $\varphi$:

$$\psi = k\varphi^n \tag{4.1}$$

where $k$ (the 'constant' in Stevens' power law) and $n$ (the 'exponent') are assumed to be constant at any frequency. With whole-body vibration of seated persons the exponent depends on the frequency of vibration (Morioka and Griffin, 2006b).

At each frequency, values of the exponent, $n$, and the constant, $k$, were determined by linear regression between the logarithms of the magnitude estimates $\log(\psi)$ and the vibration acceleration $\log(\varphi)$ using bisquare weights to reduce bias from outlier values (Section 3.4.3):

$$\log(\psi) = \log(k) + n\log(\varphi) \tag{4.2}$$

Table 4.6: Characteristics of the subjects who participated in the study with vertical vibration. Subjects 1 to 10 also participated in the study with horizontal vibration.

| Subject | Gender | Age | Height (cm) | Weight (kg) | Shoe size |
|---|---|---|---|---|---|
| 1 | M | 25 | 164 | 48 | 7.5 |
| 2 | M | 28 | 177 | 88 | 10 |
| 3 | M | 25 | 171 | 55 | 7.5 |
| 4 | M | 30 | 184 | 89 | 10.5 |
| 5 | M | 26 | 179 | 75 | 7 |
| 6 | M | 25 | 169 | 92 | 8.5 |
| 7 | M | 27 | 179 | 71 | 9 |
| 8 | M | 24 | 185 | 79 | 8.5 |
| 9 | M | 27 | 176 | 67 | 8 |
| 10 | M | 27 | 175 | 67 | 9 |
| 11 | M | 26 | 187 | 87 | 10 |
| 12 | M | 22 | 186 | 83 | 9.5 |
| 13 | M | 20 | 182 | 75 | 8.5 |
| 14 | M | 29 | 170 | 71 | 8.5 |
| 15 | M | 23 | 176 | 59 | 9 |
| 16 | M | 23 | 175 | 71 | 8 |

For each subject, equivalent comfort contours were obtained for different subjective magnitudes, $\psi$, using individual values of $k$ and $n$ (which depend on frequency):

$$\varphi = \left(\frac{\psi}{k}\right)^{\frac{1}{n}} \tag{4.3}$$

This equation gives the acceleration, $\varphi$, needed at each frequency to achieve a given level of discomfort, $\psi$. For horizontal vibration, equivalent comfort contours were constructed for magnitude estimates of 100 (i.e. equivalent to the reference motion in the same direction), and for magnitude estimates of 130 and 160. For vertical vibration, contours were constructed for magnitude estimates of 120, 150 and 180. These levels were chosen so that the equivalent comfort contours were within the range of stimuli presented to the subjects, as shown in Figure 4.6. Values outside this range would be based on extrapolation.

The equivalent comfort contours corresponding to the magnitude estimates in the middle of the range (130 for horizontal vibration, and 150 for vertical vibration) were used to derive frequency weightings (see Figure 4.6). For each axis, the equivalent comfort contour was inverted, and then multiplied by an arbitrary constant to assist comparison with the frequency weightings advocated in the standards. The weightings for horizontal vibration were adjusted so that they correspond to the weighting $W_d$ at 16 Hz (the multiplying factor was 0.12). The weighting for vertical vibration was adjusted so that it corresponded to the weighting $W_b$ over the range 2 to 16 Hz (the multiplying factor was 0.5).

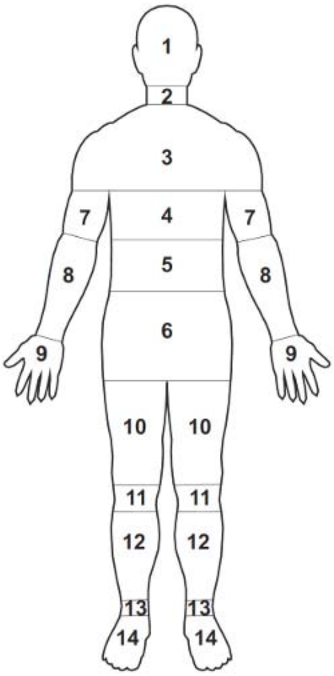


Figure 4.3: Body map used in the experiment.

The procedure used for the data analysis is summarized in Figure 4.4.

### 4.2.7 Statistical tests

Non-parametric tests (the Friedman two-way analysis of variance by ranks, the Wilcoxon matched-pairs signed ranks test, the Spearman rank-order correlation coefficient, the McNemar change test and the Cochran Q test) were employed in the statistical analysis.

## 4.3 Results

### 4.3.1 Growth of sensation

The median values of the constant ($k$) and the exponent ($n$) in Stevens' power law (Equation 4.1), used to construct equivalent sensation contours and frequency weightings are reported in Table 4.7.

The median rate of growth of discomfort, also called the 'exponent', is also shown for all three directions of vibration in Figure 4.5 with inter-quartile ranges.

With fore-and-aft vibration, over the range 0.5 to 16 Hz the exponent was dependent on the frequency of vibration ($p < 0.001$, Friedman). The exponent was least from 5 to 8 Hz, and over the range 0.5 to 4 Hz the exponent was not significantly dependent on the frequency of vibration ($p = 0.079$, Friedman).

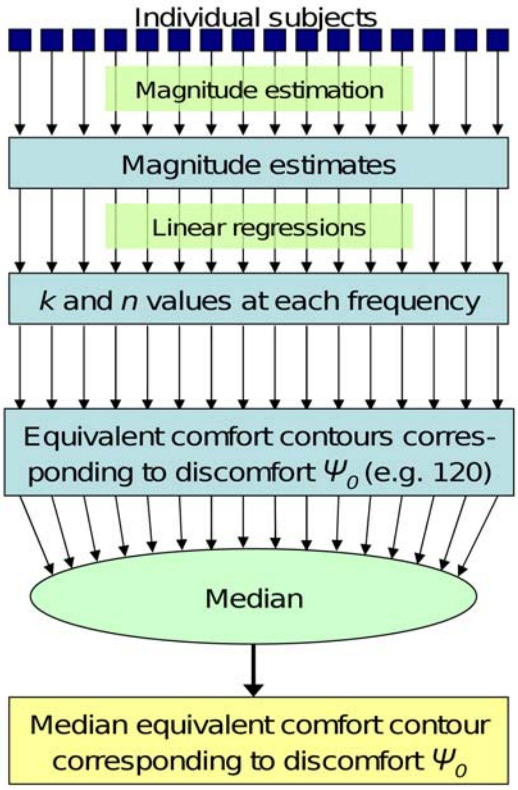


Figure 4.4: Summary of the data analysis procedure.

With lateral vibration, the exponent was independent of frequency ($p = 0.085$, Friedman).

With vertical vibration, over the range 0.5 to 16 Hz the exponent was dependent on the frequency of vibration ($p < 0.001$, Friedman). Multiple comparisons showed that the exponent at any frequency in the range 0.5 to 4 Hz was greater than that at any frequency in the range 5 to 16 Hz ($p < 0.05$, Wilcoxon). Over the range 5 to 16 Hz, the exponent did not depend on frequency ($p = 0.220$, Friedman). As shown in Figure 4.5, the median exponent tends to decrease from 0.5 to 4 Hz but is relatively constant from 5 to 16 Hz.

### 4.3.2 Equivalent comfort contours

Equivalent sensation contours corresponding to magnitude estimates of 100, 130, and 160 for horizontal vibration, and 120, 150 and 180 for vertical vibration, are shown in Figure 4.6, together with the range of magnitudes used in the experiment. In all three directions, the acceleration on each contour depended on frequency ($p < 0.05$, Friedman), so sensitivity to acceleration depended on the frequency of vibration with each direction of vibration.

Equivalent comfort contours in terms of velocity were also constructed (Figure 4.7). They were derived from the acceleration contours using the equation (which is valid for sinusoidal motions):

Table 4.7: Median values of the constant ($k$) and exponent ($n$) in Stevens' power law, at different frequency of fore-and-aft, lateral and vertical vibration.

| Frequency (Hz) | $k$ | | | $n$ | | |
|---|---|---|---|---|---|---|
| | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ |
| 0.5 | 832 | 555 | 319 | 0.94 | 0.60 | 1.46 |
| 0.63 | 575 | 350 | 235 | 0.73 | 0.58 | 1.46 |
| 0.8 | 632 | 353 | 198 | 0.82 | 0.65 | 1.52 |
| 1 | 446 | 353 | 181 | 0.91 | 0.79 | 1.17 |
| 1.25 | 326 | 274 | 166 | 0.82 | 0.71 | 1.20 |
| 1.6 | 289 | 256 | 136 | 0.70 | 0.70 | 0.97 |
| 2 | 252 | 199 | 151 | 0.66 | 0.65 | 1.12 |
| 2.5 | 199 | 163 | 146 | 0.67 | 0.51 | 0.79 |
| 3.15 | 177 | 170 | 175 | 0.68 | 0.61 | 0.91 |
| 4 | 182 | 159 | 204 | 0.65 | 0.58 | 0.83 |
| 5 | 164 | 145 | 210 | 0.47 | 0.68 | 0.55 |
| 6.3 | 145 | 149 | 241 | 0.57 | 0.48 | 0.41 |
| 8 | 126 | 153 | 220 | 0.51 | 0.53 | 0.61 |
| 10 | 128 | 148 | 205 | 0.58 | 0.53 | 0.56 |
| 12.5 | 127 | 140 | 224 | 0.69 | 0.57 | 0.64 |
| 16 | 119 | 143 | 218 | 0.86 | 0.67 | 0.49 |

$$a_{\text{r.m.s.}} = 2\pi f v_{\text{r.m.s.}} \tag{4.4}$$

where $f$ is the vibration frequency and $a_{\text{r.m.s.}}$ and $v_{\text{r.m.s.}}$ are the r.m.s. acceleration and velocity, respectively.

With both fore-and-aft and lateral vibration, when each of the three equivalent comfort contours were expressed in terms of vibration velocity they were independent of the frequency of vibration over the range 0.5 to 2.5 Hz ($p > 0.16$, Friedman), suggesting the contours have constant velocity in this range.

With vertical vibration, the equivalent contours expressed in terms of vibration acceleration suggest sensitivity is greatest in the range 5 to 16 Hz. The shapes of the contours depend on the magnitude of vibration, consistent with the dependence of the exponent, $n$, on the frequency of vibration (Section 4.3.1).

### 4.3.3 Frequency weightings

For all three axes of vibration, frequency weightings were derived from the equivalent comfort contours (as explained in Section 4.2.5). The weightings obtained for horizontal vibration are shown in Figure 4.8, with the weighting $W_d$, advocated in the standards for evaluating horizontal vibration. A weighting corresponding to constant velocity at low

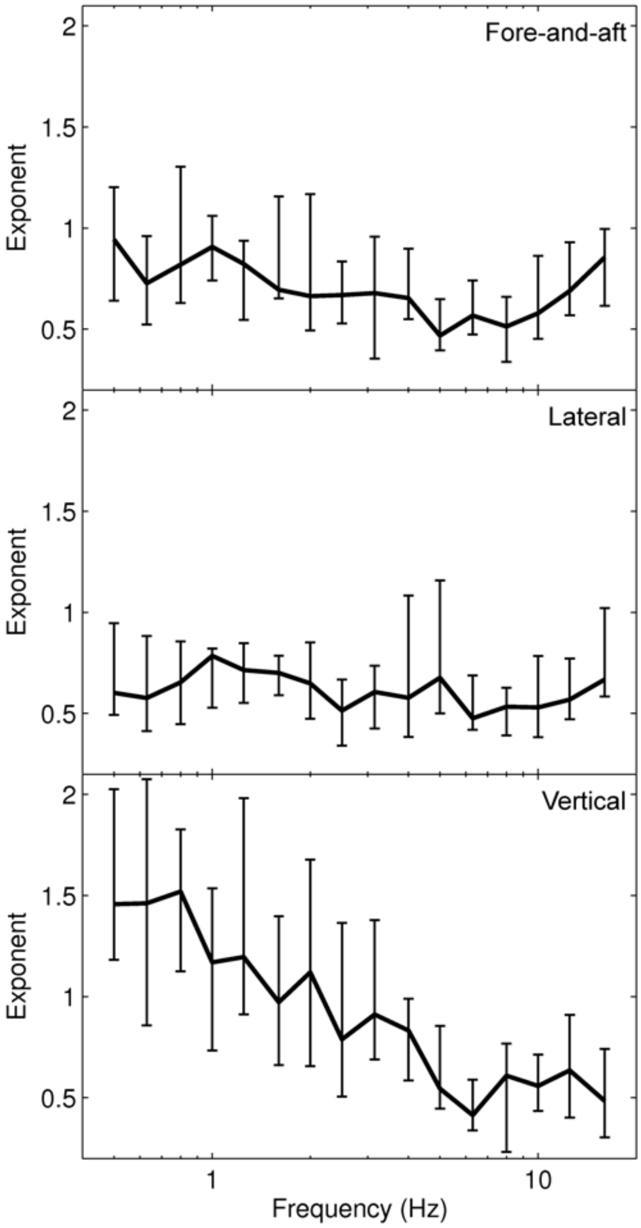


Figure 4.5: Median rates of growths of sensation at each frequency and in each axis of motion, and interquartile ranges for all 16 subjects (for data, see Appendix E.1, Table E.1).

frequencies and constant acceleration at high frequencies, with a transition at 3.15 Hz, is also shown, with its asymptotic approximation (see Chapter 10).

The weighting obtained for vertical vibration is shown in Figure 4.9 and compared with the weighting $W_b$ advocated in standards for evaluating vertical vibration. A weighting has also been constructed by multiplying $W_b$ by an all-pass filter corresponding to constant acceleration at frequencies lower than 1 Hz, and constant acceleration at greater frequencies (see Chapter 10).

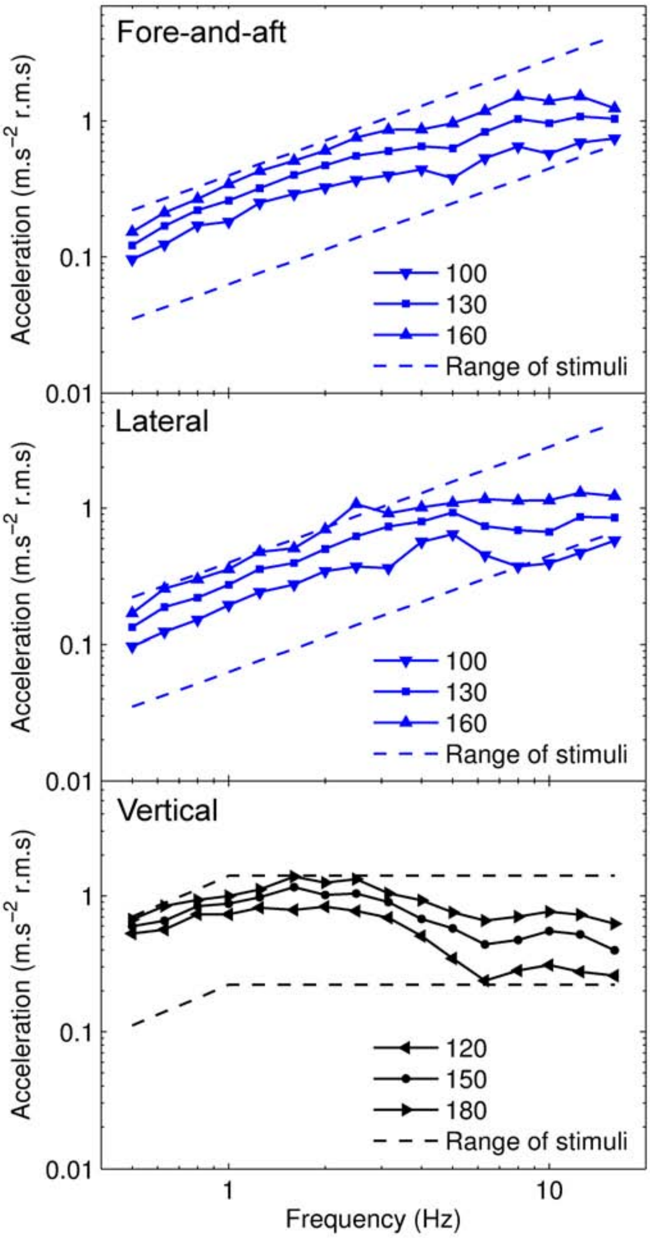


Figure 4.6: Equivalent sensation contours constructed for all three axes of motion, corresponding to different magnitude estimates (for data, see Appendix E.2, Table E.2).

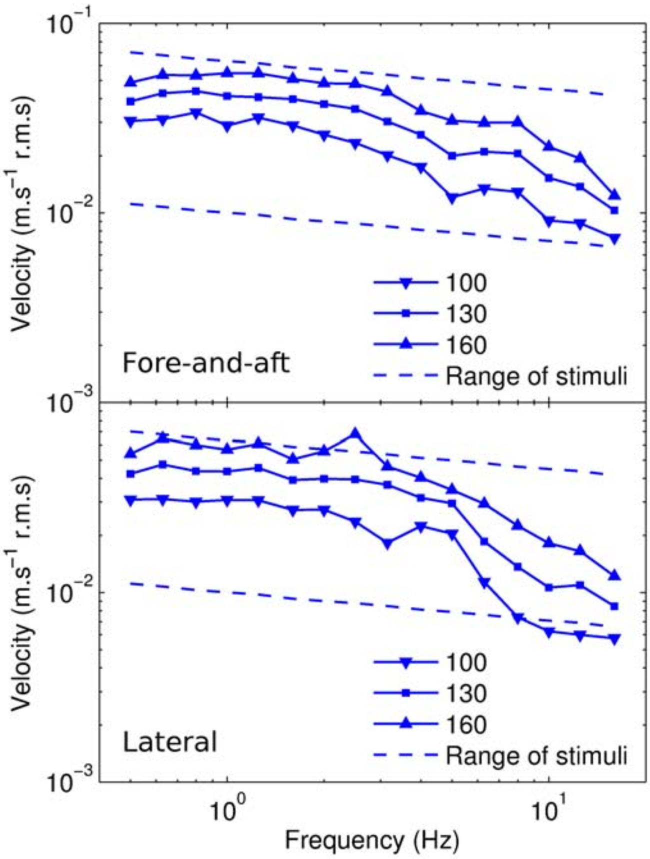


Figure 4.7: Equivalent sensation contours for horizontal vibration expressed in terms of velocity.

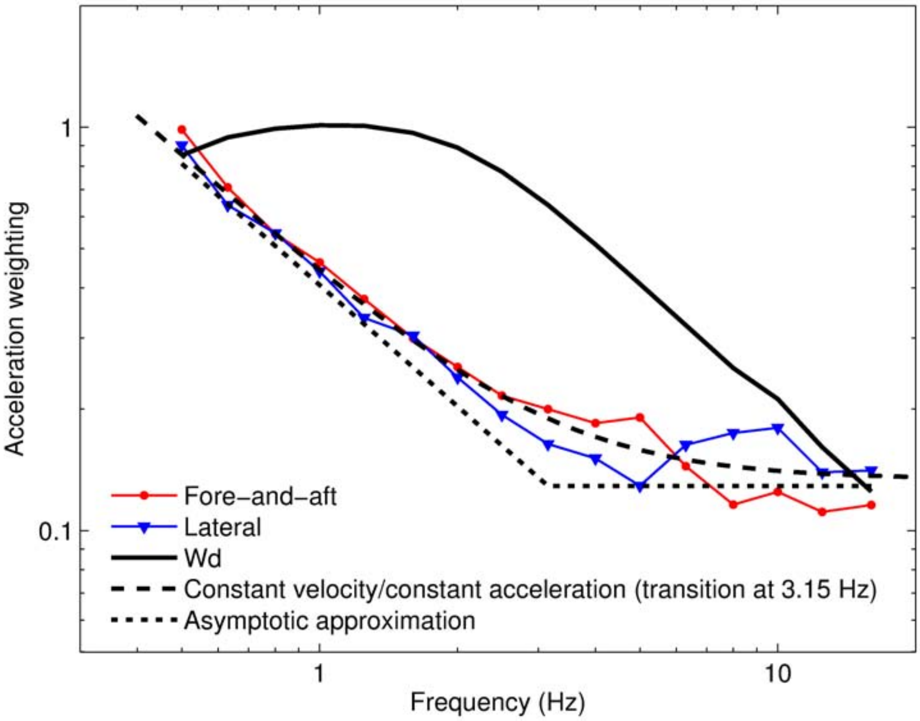


Figure 4.8: Comparison of the frequency weightings obtained in the experiment with the weightings advocated in standards for horizontal vibration.

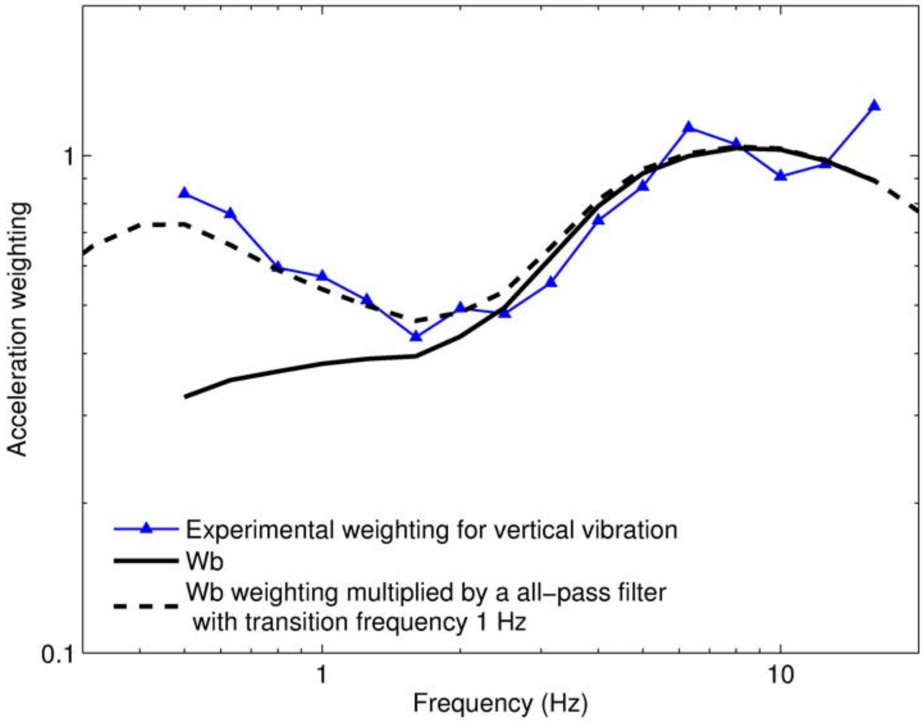


Figure 4.9: Comparison of the frequency weighting obtained in the experiment with the weightings advocated in standards for vertical vibration.

### 4.3.4 Cause of discomfort

The main causes of discomfort reported by the subjects for the three axes of motion are shown in Figure 4.10 at each frequency and in each direction, summarized for both magnitudes (3 and 7). The colour of each body part represents the number of subjects who reported discomfort in that particular area. The area around the subject corresponds to causes of discomfort that are not localized, i.e., in the case of horizontal vibration, loss of stability. The data is also summarized in Figure 4.11. At each frequency of horizontal vibration and at both magnitudes of vibration, the proportions of subjects reporting the main cause of discomfort as vibration in the legs and feet, vibration in the upper-body, or balance disturbance are shown.

With both axes of horizontal vibration, and at both magnitudes, the number of subjects reporting balance as the main cause of discomfort and the number of subjects reporting vibration in the lower body as the main cause of discomfort were dependent on the frequency of vibration ($p < 0.05$, Cochran). As the frequency of vibration increased, the discomfort caused by vibration in the legs and feet tended to increase, and the discomfort caused by loss of balance tended to decrease.

With vertical vibration, the proportions of subjects reporting vibration in the legs and feet, vibration in the upper-body, or a different cause of discomfort, are also shown in Figure 4.11. The ‘different’ causes of discomfort were not specified explicitly but may have included vestibular excitation as they occurred at low frequencies but not in a specific

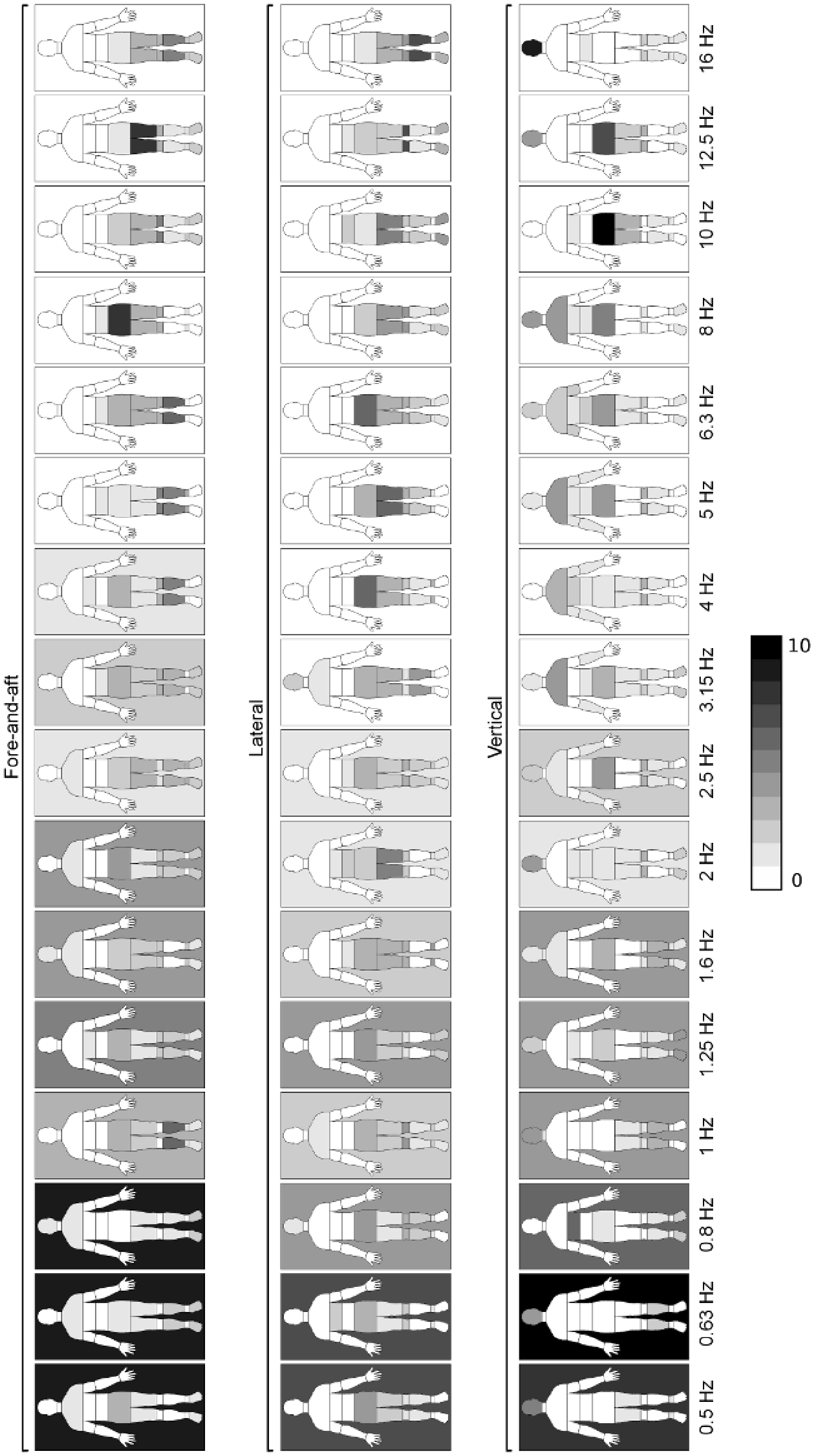


Figure 4.10: Localization of discomfort in the body at each frequency and in each direction. The colour indicates the number of subjects who localized the main cause of discomfort in the corresponding body area. The area around the body refers to balance (for horizontal vibration) or other causes (vertical vibration).

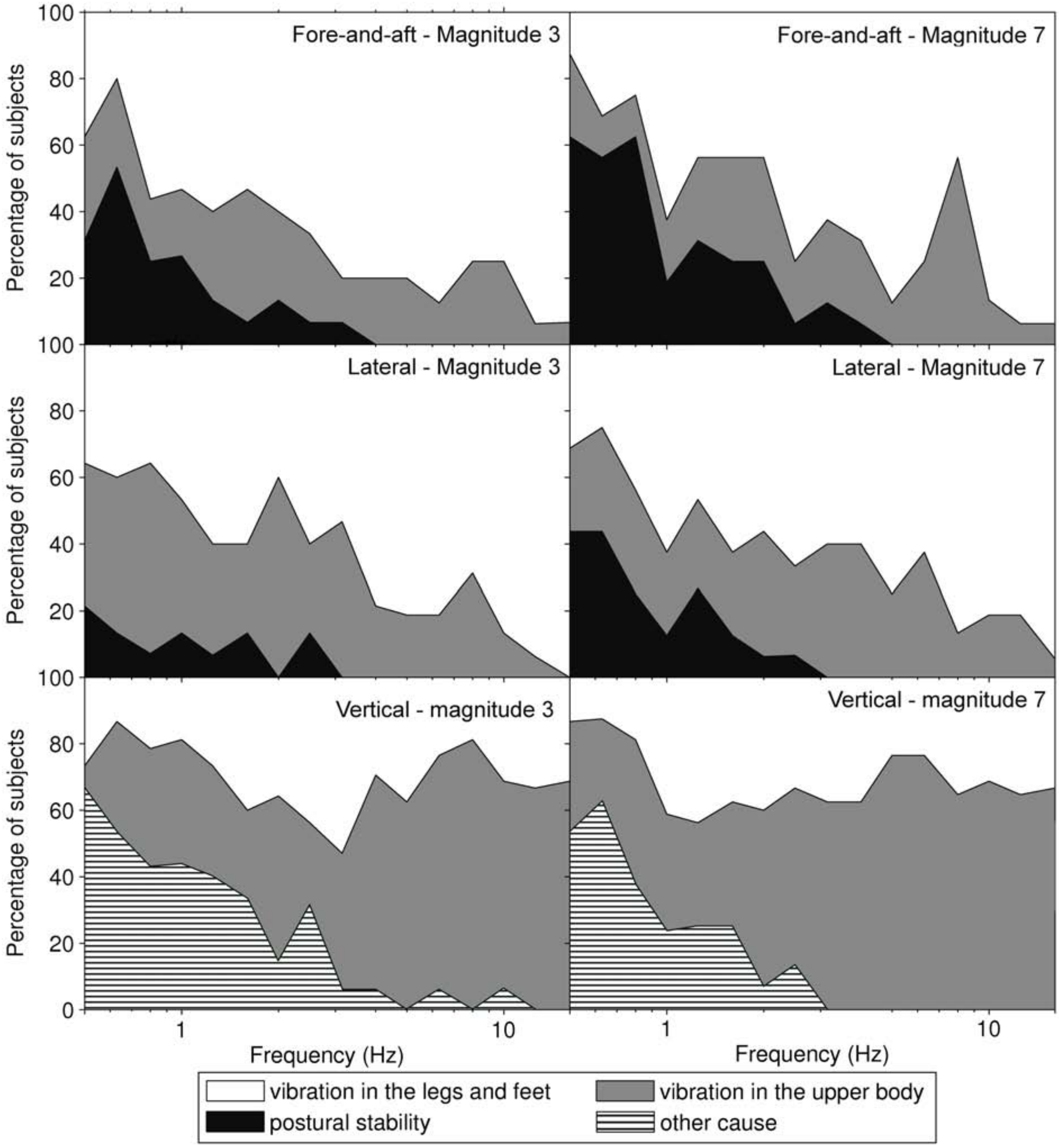


Figure 4.11: Proportion of subjects reporting different factors as the main cause of discomfort (for data, see Appendix E.3, Tables E.5 and E.4).

part of the body. The cause of discomfort for low-frequency vertical vibration is further investigated in Chapter 7. At both magnitudes, the importance of vertical vibration in the legs was independent of the frequency of vibration ($p > 0.14$, Cochran).

## 4.4 Discussion

### 4.4.1 Equivalent comfort contours

Equivalent-sensation contours have previously been constructed for standing people exposed to vertical vibration by Chaney (1965), Jones and Saunders (1972), Ashley (1970), Oborne and Clarke (1974) and Miwa (1967b and 1968c), and are compared with the equivalent comfort contours from the present study in Figure 4.12. The studies used different psychophysical methods and different environmental conditions, so differences can be expected. However, all contours suggest greatest sensitivity to vertical acceleration between 5 and 8 Hz (Figure 4.12), except those obtained by Miwa (1967-part1).

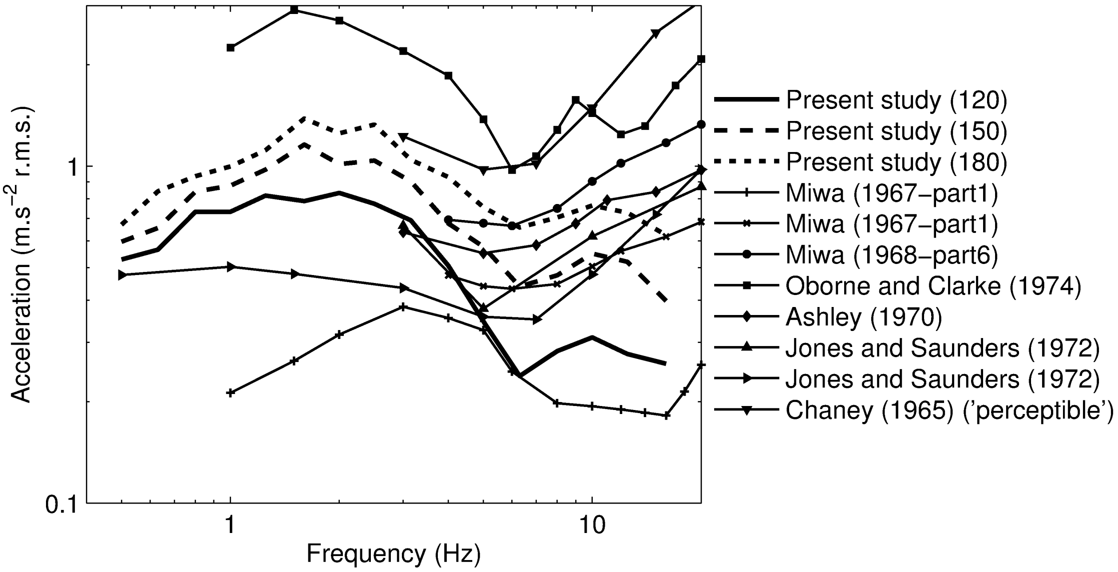


Figure 4.12: Comfort contours obtained in the present study with vertical vibration for the magnitude estimates '100', '140' and '200', and by previous researchers.

In the present study, with vertical vibration, the rate of growth of sensation was least, and sensitivity to low magnitude acceleration was greatest, at 6.3 Hz, within the range of greatest sensitivity found in previous studies. Investigating the apparent masses of standing subjects exposed to random vertical vibration over the range 2 to 20 Hz, Subashi *et al.* (2006) found the first resonance frequency at 6.39 Hz, 6.01 Hz, and 5.63 Hz when using vibration magnitudes of 0.125, 0.25, and 0.5 m.s$^{-2}$ r.m.s., respectively. It seems reasonable to assume that the increased sensitivity to vertical vibration at 6.3 Hz found in the present study may be associated with body resonance around this frequency.

### 4.4.2 Frequency weightings

British Standard 6841 (1987), European prestandard ENV 12299 (1999), and International standard ISO 2631-1 (1997) provide frequency weightings for evaluating vibration with respect to the discomfort of standing persons. For lateral and fore-and-aft vibration, all three standards advocate frequency weighting $W_d$ for predicting the vibration discomfort of both seated and standing people. For vertical vibration, British Standard 6841 (1987) and European prestandard ENV 12299 (1999) advocate weighting $W_b$, whereas International standard ISO 2631-1 (1997) promotes weighting $W_k$, which is similar to $W_b$; however, the recommendation in ISO 2631-1 (1997) is ambiguous since an annex to ISO 2631-1 states that in some environments, including railway vehicles, $W_b$ is considered the appropriate weighting (Appendix C, Section C.2.2.1, Note).

For standing people exposed to horizontal vibration, whereas the standards advocate weighting $W_d$ (corresponding to constant acceleration from 0.5 to 2.0 Hz and constant velocity from 2.0 to 16 Hz), the weightings obtained in this experiment correspond to constant velocity from 0.5 Hz to 3.15 Hz and constant acceleration from 3.15 Hz to 16 Hz, as shown by the similarity between the weightings and the dashed line in Figure 4.8. There is therefore little agreement between the present data and the recommendation in the standards for standing people exposed to horizontal vibration. This also implies that seated and standing persons have different responses to horizontal vibration, since the standard weighting was based on findings from studies with seated subjects.

For standing people exposed to vertical vibration at frequencies greater than 1.6 Hz, the weighting curve derived from the current results is consistent with the weighting $W_b$ advocated in the standards (Figure 4.8). This suggests that the responses of standing and seated people to vertical vibration are similar. However at lower frequencies, $W_b$ seems to underestimate the sensitivity of standing passengers. A frequency weighting has been constructed matching the experimental results, by multiplying the frequency weighting $W_b$ by an all-pass filter of cut-off frequency 1 Hz.

### 4.4.3 Cause of discomfort

Standing people can resist the destabilizing influence of gravity if their centre of mass is positioned above their base of support. Otherwise, a step or the help of a support is needed to avoid loss of balance (Nashner, 1997). Horizontal motion of a floor will therefore not be expected to cause loss of balance if the displacement of the centre of mass is not sufficient for it to approach the limits of the base of support. Although the transmissibility between the floor and the centre of mass of the body is not known, the transmissibility to the head has been measured, and it may be reasonable to assume that the motion of the head is related to the motion of the centre of mass. The transmissibility from the floor to the heads of standing subjects exposed to vibration in all three axes of translational vibration has been reported by Paddan and Griffin (1993a), with full data reported by Paddan and Griffin (1993b). The transmissibility of standing subjects exposed to fore-and-aft, lateral, and vertical vibration in conditions similar to those of the present experiment are shown in Figure 4.13.

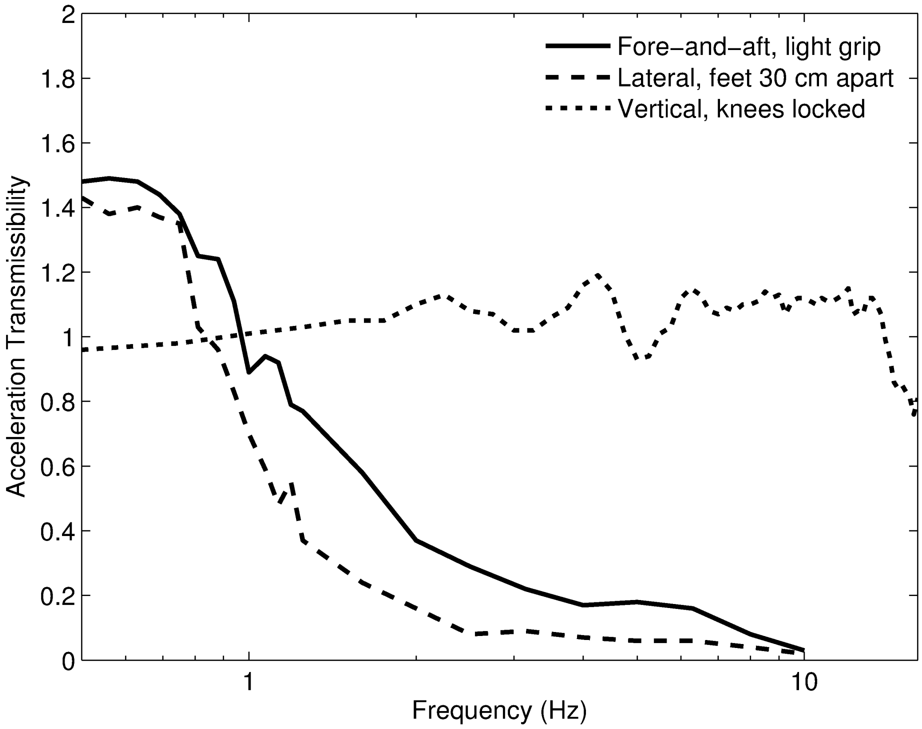


Figure 4.13: Floor-to-head transmissibility of standing people measured by Paddan and Griffin (1993b).

The fore-and-aft and lateral transmissibilities are greatest at frequencies between about 0.5 and 0.8 Hz, and decrease as the frequency increases from 0.8 Hz to 10 Hz, similar to the trend in the importance of balance disturbance as a source of discomfort (Figure 4.11). The importance of vibration in the legs increases with increasing frequency, consistent with the decrease in the transmission of vibration to the upper-body with increasing frequency. With vertical vibration, the importance of vibration in the legs as a source of vibration discomfort did not change with frequency (Figure 4.11), consistent with vertical transmissibility being independent of frequency over this range (Figure 4.13). This is consistent with the results of Landström and Lundström (1986), who found that even at frequencies as high as 8 and 16 Hz, standing people experienced discomfort in upper-body areas, such as the lumbar region, abdominal region, shoulders, and face.

### 4.4.4 The frequency-dependence of discomfort of standing people

From the frequency-dependence of both sensitivity to vibration and causes of discomfort, it appears that the responses of the subjects were different at lower and higher frequencies.

With fore-and-aft and lateral vibration, subject sensitivity seems to depend on vibration velocity at frequencies less than about 3.15 Hz, and vibration acceleration at frequencies greater than about 3.15 Hz, as shown by the equivalent comfort contours and the frequency weightings (Figures 4.8 and 4.9). Over the range 0.5 to 3.15 Hz, at least some of the discomfort was caused by balance disturbance (Figure 4.11), suggesting that the disturbance of the stability of standing people may depend on vibration velocity; this is consistent with the loss of balance in walking subjects exposed to transient lateral motions at frequencies between 0.5 and 2 Hz, which is correlated with the velocity of the motion (Sari and Griffin, 2009).

With vertical vibration, the rate of growth of discomfort was different at low and high frequencies (Figure 4.5): at frequencies less than 4 Hz, the exponent decreased steadily as frequency increased, whereas at frequencies greater than 4 Hz it remained approximately constant. The analysis of the causes of discomfort show that in the range 0.5 Hz to 4 Hz, some subjects did not feel discomfort in a specific part of the body. These findings suggest that, as with horizontal vibration, the principal mechanisms for the perception of vibration differ between frequencies less than 4 Hz and frequencies greater than 4 Hz.

## 4.5 Conclusions

The rate of growth of sensation, the shapes of equivalent comfort contours and the causes of discomfort are similar for fore-and-aft and lateral vibration. For both axes, the frequency weightings correspond to constant velocity at lower frequencies (where loss of balance is a cause of discomfort) and constant acceleration at higher frequencies (where loss of balance is not a cause of discomfort), with a transition at about 3.15 Hz. This is not consistent with the weighting advocated in current standards (i.e. $W_d$) that was based on studies with seated subjects.

The equivalent comfort contours for vertical vibration are consistent with the weighting advocated in standards (i.e. $W_b$) except at frequencies less than 1.6 Hz. Subjects were particularly sensitive to vibration at frequencies in the range 4 to 16 Hz, with greatest sensitivity to low magnitude acceleration around 6.3 Hz, possibly due to a resonance of the body.

Comparisons with the weightings advocated in the standards suggest that the responses of standing and seated people are similar when exposed to vertical vibration, except at lower frequencies where vibration was probably perceived through the vestibular system. the responses of standing and seated people were different when exposed to horizontal vibration. For all three axes of excitation, different mechanisms are responsible for discomfort caused by low frequency and high frequency vibration (i.e. less than or greater than 3 or 4 Hz).

From the experimental results, frequency weightings that can be used for evaluating vibration so as to predict the discomfort of standing people exposed to fore-and-aft, lateral, or vertical vibration have been constructed.

# Chapter 5

# Relative sensitivity to vibration in the fore-and-aft, lateral, and vertical direction

## 5.1 Introduction

In Chapter 4, frequency weightings were constructed to represent the frequency-dependence of the discomfort of standing people. The weightings were based on experimental observation of the effect of frequency on discomfort in each direction: fore-and-aft, lateral and vertical. However, no comparison was made between the directions. That means the study reported in Chapter 4 provided weightings that are valid within a direction, but not between directions, as they did not take account of the relative sensitivity between axes. It was therefore necessary to conduct a study investigating the relative sensitivity between directions, in order to adjust the frequency weightings relative to each other and achieve inter-axis validity.

In International standards and British standards, the effect of lateral and fore-and-aft vibration is assumed to be identical. The experiment designed in this chapter investigated this hypothesis, and more generally compared the effect of vibration in different directions to obtain a quantitative measure of the relative sensitivity in different directions at a single frequency, in order to adjust the frequency weightings obtained in Chapter 4 and provide weightings that can be used to evaluate and compare motions which are not in the same direction.

## 5.2 Method

### 5.2.1 Motions

All motions were 4-Hz sinusoidal vibrations of 6-seconds duration in either the fore-and-aft, the lateral, or the vertical direction. The motions were always presented in pairs. Each pair consisted of a reference motion followed by a test motion. The reference motion and the test motion were always in different directions. Vibration pairs were divided in six different groups, as shown in Table 5.1.

Table 5.1: The six groups of stimuli pairs.

| **Group** | **Direction of reference motion** | **Direction of test motions** |
|---|---|---|
| 1 | Fore-and-aft | Lateral |
| 2 | Fore-and-aft | Vertical |
| 3 | Lateral | Fore-and-aft |
| 4 | Lateral | Vertical |
| 5 | Vertical | Fore-and-aft |
| 6 | Vertical | Lateral |

In each group, the reference motion was presented at a constant magnitude, and the test motions were presented at 10 magnitudes in steps of 1.5 dB. The magnitudes of the reference motions and the test motions for each direction are reported in Table 5.2. Based on a preliminary study, the magnitudes were chosen so that the stimuli caused approximately equivalent discomfort in all three directions. Compared to the fore-and-aft stimuli, the magnitudes of the reference and the test stimuli were 2 dB lower in the lateral direction and 2 dB higher in the vertical direction.

Table 5.2: Magnitudes of motions (all magnitudes are in m.s$^{-2}$ r.m.s.).

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| Reference | 0.5 | 0.63 | 0.32 |
| Test magnitude 1 | 0.23 | 0.29 | 0.15 |
| Test magnitude 2 | 0.27 | 0.34 | 0.17 |
| Test magnitude 3 | 0.32 | 0.41 | 0.2 |
| Test magnitude 4 | 0.39 | 0.49 | 0.24 |
| Test magnitude 5 | 0.46 | 0.58 | 0.29 |
| Test magnitude 6 | 0.55 | 0.69 | 0.34 |
| Test magnitude 7 | 0.65 | 0.82 | 0.41 |
| Test magnitude 8 | 0.77 | 0.97 | 0.49 |
| Test magnitude 9 | 0.92 | 1.15 | 0.58 |
| Test magnitude 10 | 1.09 | 1.37 | 0.69 |

### 5.2.2 Equipment

The motions were produced using a six degree-of-freedom motion simulator (Figure 5.1). The simulator can generate fore-and-aft, lateral, vertical, pitch, roll and yaw motions, with a maximum displacement range of ±250mm in the fore-and-aft and lateral directions, and ±500 mm in the vertical direction. The simulator was controlled by a Pulsar Digital Controller (Servotest Systems, Egham, UK). The motion stimuli were generated in Matlab (version R2009a) using the Matlab Toolbox HVLAB HRV (version 1.1) developed by the Human Factors Research Unit (University of Southampton).

The vibration of the platform was monitored using Setra 141A capacitive accelerometers secured to the centre of the table of the simulator. The signals from the transducers were sampled by a Pulsar Digital Controller software at 256 samples per second after low pass filtering at 64 Hz.

The performance of the simulator in terms of distortion and cross-axis coupling are reported in Chapter 3, Section 3.2.1.4.

### 5.2.3 Subjects

Twelve healthy male university students and staff with median age 26 years (range 23 to 30 y), stature 175 cm (165 to 198 cm), weight 66 kg (50 to 104 kg) participated in the study. They attended one session lasting approximately 90 minutes. The characteristics of the subjects are listed in Table 5.3.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

Table 5.3: Physical characteristics of the subjects used in the experiment.

| Subject | Gender | Age | Height (cm) | Weight (kg) |
|---|---|---|---|---|
| 1 | M | 29 | 175 | 90 |
| 2 | M | 30 | 174 | 70 |
| 3 | M | 26 | 178 | 60 |
| 4 | M | 28 | 170 | 55 |
| 5 | M | 24 | 169 | 61 |
| 6 | M | 23 | 198 | 104 |
| 7 | M | 23 | 178 | 74 |
| 8 | M | 24 | 174 | 59 |
| 9 | M | 25 | 175 | 82 |
| 10 | M | 26 | 167 | 61 |
| 11 | M | 26 | 165 | 50 |
| 12 | M | 24 | 190 | 92 |
| Median | / | 26 | 175 | 66 |

Figure 5.1: Photograph and model of the safety frame mounted on the 6-degrees-of-freedom motion simulator.

### 5.2.4 Conditions and posture

The subjects wore socks but no shoes and wore a loose harness in case they should fall (Figure 5.1). The harness did not provide support or restrict movement when subjects stood as instructed. It was attached to an extruded aluminium frame secured to table of the vibrator.

The subjects maintained an upright posture, with their knees locked, and kept their eyes closed. Their feet were parallel and separated so that their lateral 'base of support' (distance between the outer edges of their feet) was 350 mm, the median shoulder width for adult males (Pheasant, 1988).

The subjects wore headphones delivering broadband noise at 65 dB(A). The headphones also provided some acoustic isolation from external noises, and this was found sufficient to mask noises produced by the simulator when generating motions.

### 5.2.5 Procedure

During a session, subjects were exposed to 10 pairs of vibrations from each of the six groups shown in Table 5.1. Within each group, the magnitude of the reference motion was held constant, and the magnitude of the test motion took all ten values shown in Table 5.2 for the corresponding direction. The 60 pairs of motions were presented in a randomized order to minimize range effects.

In addition, the whole procedure was repeated a second time during the same session; so over a whole session, each of the 60 pairs of stimuli was presented twice. The objective was to analyze the repeatability of the measurements, and to obtain more reliable values by using the geometric mean of the two estimations obtained for each test stimulus.

The method of magnitude estimation (Chapter 3, Section 3.4.1) was employed to determine the discomfort caused the test motions. After the presentation of a pair of motions, subjects were asked to provide a number reflecting the discomfort caused by the test motion, assuming the discomfort caused by the reference motion was 100. The subjects could ask for the pair of motions to be repeated if they were not sure of their judgement. Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli (see Appendix A.2.1). This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli.

### 5.2.6 Analysis

#### 5.2.6.1 Determination of equivalent acceleration

Stevens' power law (Stevens, 1975) was used to relate the magnitude estimates of subject discomfort, $\psi$, to the physical magnitudes of the test motions, $\varphi$:

$$\psi = k\varphi^n \tag{5.1}$$

where $k$ (the 'constant' in Stevens' power law) and $n$ (the 'exponent', or rate of growth of sensation) are assumed to be constant at any frequency.

For each group of stimuli (Table 5.1) and each subject, values of the exponent, $n$, and the constant, $k$, were determined by linear regression between the logarithms of the magnitude estimates and the test vibration acceleration (10 values) using bisquare weights to reduce bias from outlier values (Section 3.4.3):

$$\log(\psi) = \log(k) + n\log(\varphi) \tag{5.2}$$

Once the values of $k$ and $n$ were determined, Equation (5.1) could be rewritten as follows:

$$\varphi = \left(\frac{\psi}{k}\right)^{\frac{1}{n}} \tag{5.3}$$

So, for each subject and each group, the magnitude of the test motion equivalent in discomfort to the reference motion (i.e., corresponding to a magnitude estimate of 100) could be determined as shown in Equation (5.4).

$$a_{eq}(\text{ref\_axis,test\_axis}) = \left(\frac{100}{k}\right)^{\frac{1}{n}} \tag{5.4}$$

#### 5.2.6.2 Equivalence coefficients

The relative sensitivity to vibration in the test axis compared to the reference axis can be estimated by the ratio of the magnitude of the reference motion to this equivalent magnitude, which will be referred to as the 'equivalence coefficient', $K(a,b)$:

$$K(\text{ref-axis, test-axis}) = \frac{a_{ref}(\text{ref-axis})}{a_{eq}(\text{ref-axis, test-axis})} \tag{5.5}$$

This coefficient is an estimate of the relative sensitivity to vibration in the test axis compared to the reference axis. For example, since the magnitude of the reference vibration in the $x$-axis was 0.5 m.s$^{-2}$ r.m.s., a value of $K(x, y) = 2$ indicates that 0.25 m.s$^{-2}$ in the y-axis causes the same discomfort as 0.5 m.s$^{-2}$ in the x-axis. That suggests that the subject is twice as sensitive to lateral vibration as to fore-and-aft vibration. Conversely, a value of $K(x, y)$ less than 1 indicates that the subject is less sensitive to $y$-axis vibration than to $x$-axis vibration.

#### 5.2.6.3 Construction of inter-axis coefficients

There is one issue with the equivalence coefficients $K$ calculated with Equation (5.5). These estimates can be biased, particularly by a possible order effect. For example, subjects may systematically overestimate the magnitude of the second motion when exposed to a test-reference pair of stimuli (this effect is investigated in Section 5.4.1). For this reason, in order to cancel out such bias, for each pair of directions ($x/y$, $x/z$ and $y/z$), the procedure was repeated in both orders, as shown in Table 5.1 ($x/y$ and $y/x$; $x/z$ and $z/x$; $y/z$ and $z/y$) so that a possible bias could be cancelled out by averaging the results. So, new unbiased estimates of the relative sensitivities $K_2$ were obtained as shown in Equations (5.6), (5.7) and (5.8):

$$K_2(x, y) = \frac{1}{K_2(y, x)} = \sqrt{\frac{K(x, y)}{K(y, x)}} \tag{5.6}$$

$$K_2(x, z) = \frac{1}{K_2(z, x)} = \sqrt{\frac{K(x, z)}{K(z, x)}} \tag{5.7}$$

$$K_2(y, z) = \frac{1}{K_2(z, y)} = \sqrt{\frac{K(y, z)}{K(z, y)}} \tag{5.8}$$

There is another issue with the $K_2$ coefficients. Since they are supposed to provide a comparison of the sensitivity to vibration between directions, they should be consistent, in the sense that:

$$K_3(x, z) = K_3(x, y) \cdot K_3(y, z) \tag{5.9}$$

The condition in Equation (5.9) is generally not verified due to noise in the measurement. The need for this condition to be verified, and the desire to obtain formulae that are symmetrical for all three directions, lead to building consolidated coefficients as shown in Equations (5.10), (5.11) and (5.12):

$$K_3(x,y) = \left\{K_2(x,y)^2 \cdot [K_2(x,z) \cdot K_2(z,y)]\right\}^{\frac{1}{3}} \tag{5.10}$$

$$K_3(x,z) = \left\{K_2(x,z)^2 \cdot [K_2(x,y) \cdot K_2(y,z)]\right\}^{\frac{1}{3}} \tag{5.11}$$

$$K_3(y,z) = \left\{K_2(y,z)^2 \cdot [K_2(y,x) \cdot K_2(x,z)]\right\}^{\frac{1}{3}} \tag{5.12}$$

#### 5.2.6.4 Inter-axis coefficients

If the estimates $K_2$ are replaced with their expressions (Equations 5.6, 5.7, and 5.8) in Equations (5.10), (5.11) and (5.12), the expressions of the relative sensitivities between the three directions are obtained, as shown in Equations (5.13), (5.14) and (5.15). They will be called 'inter-axis coefficients'.

$$K_3(x,y) = \left[\left(\frac{K(x,y)}{K(y,x)}\right)^2 \cdot \frac{K(z,y) \cdot K(x,z)}{K(y,z) \cdot K(z,x)}\right]^{\frac{1}{6}} \tag{5.13}$$

$$K_3(x,z) = \left[\left(\frac{K(x,z)}{K(z,x)}\right)^2 \cdot \frac{K(y,z) \cdot K(x,y)}{K(z,y) \cdot K(y,x)}\right]^{\frac{1}{6}} \tag{5.14}$$

$$K_3(y,z) = \left[\left(\frac{K(y,z)}{K(z,y)}\right)^2 \cdot \frac{K(x,z) \cdot K(y,x)}{K(z,x) \cdot K(x,y)}\right]^{\frac{1}{6}} \tag{5.15}$$

Equations (5.13), (5.14) and (5.15) are consistent with each other: Equation (5.15) can be obtained by dividing Equation (5.14) by Equation (5.13). To obtain 'global' values for inter-axis coefficients, the median values of the individual 'equivalence coefficients' $K$ were used in Equations (5.13) and (5.14). Alternatively, $K_3$ coefficients could have been calculated for each subject to calculate the median $K_3$. However, if that method had been used, the condition in Equation (5.9) would not necessarily be verified by the median $K_3$ coefficients.

The ratio in Equation (5.13) represents the relative sensitivity to lateral vibration compared to fore-and-aft vibration. For example, a ratio of 2.0 means that the discomfort caused by a fore-and-aft vibration with magnitude 1.0 m.s$^{-2}$ r.m.s. will be equivalent to that caused by a lateral vibration with magnitude 0.5 m.s$^{-2}$ r.m.s. This means that in order to compare a 4-Hz fore-and-aft vibration with a 4-Hz lateral vibration, the weighting applied to the lateral vibration should be twice the weighting applied to the fore-and-aft vibration.

Practically, if frequency weightings are used to evaluate vibrations in different directions, the ratio of the 'lateral' weighting to the 'fore-and-aft' weighting at 4 Hz should be equal to the coefficient calculated with Equation (5.13). Similarly, the ratio of the 'vertical' weighting to the 'fore-and-aft' weighting at 4 Hz should be equal to the coefficient calculated with Equation (5.14).

Frequency weightings obtained in Chapter 4 were modified in view of the results of the present study, to construct frequency weighting taking into account the relative sensitivity between different directions; they were multiplied by constants so that the ratios of the weightings at 4 Hz reflect the relative sensitivities obtained in the experiment.

The procedure used for the data analysis is summarized in Figure 5.2.

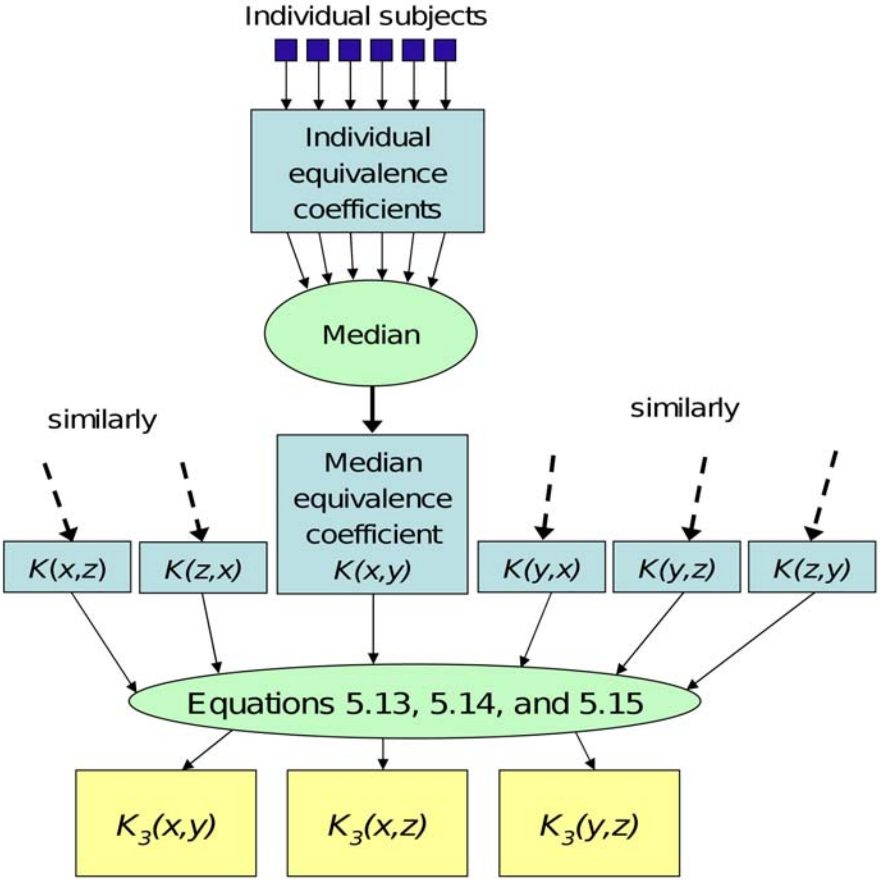


Figure 5.2: Summary of the data analysis procedure.

## 5.3 Results

### 5.3.1 Equivalence coefficients

The equivalence coefficients calculated with Equation (5.5), are reported in Table 5.4 for each subject and all six groups. When a coefficient was less than 1.0, the inverse coefficient was greater than 1.0, and reciprocally. This was predictable: for example, $K(x, y) < 1$ would suggest that people are less sensitive to lateral vibration than to fore-and-aft vibration and $K(y, x) > 1$ has the same meaning.

Table 5.4: Equivalence coefficients calculated with Equations (5.4) and (5.5) using the geometric mean of the two estimations obtained for each test stimulus for each subject.

| | $K(x, y)$ | $K(y, x)$ | $K(y, z)$ | $K(z, y)$ | $K(z, x)$ | $K(x, z)$ |
|---|---|---|---|---|---|---|
| Subject 1 | 0.76 | 1.72 | 3.65 | 0.35 | 0.64 | 2.52 |
| Subject 2 | 0.52 | 1.54 | 3.47 | 0.27 | 0.48 | 1.78 |
| Subject 3 | 0.46 | 1.02 | 3.54 | 0.28 | 0.32 | 1.62 |
| Subject 4 | 0.68 | 1.23 | 1.90 | 0.05 | 0.64 | 1.60 |
| Subject 5 | 0.54 | 1.34 | 2.06 | 0.36 | 0.53 | 1.41 |
| Subject 6 | 0.73 | 1.45 | 2.40 | 0.33 | 0.55 | 1.74 |
| Subject 7 | 0.74 | 1.16 | 2.20 | 0.41 | 0.45 | 1.92 |
| Subject 8 | 0.54 | 1.01 | 2.11 | 0.28 | 0.4 | 1.50 |
| Subject 9 | 1.03 | 1.73 | 3.43 | 0.51 | 0.61 | 3.52 |
| Subject 10 | 0.91 | 0.94 | 2.05 | 0.65 | 0.55 | 1.48 |
| Subject 11 | 0.57 | 1.57 | 4.17 | 0.27 | 0.49 | 2.56 |
| Subject 12 | 0.80 | 1.11 | 4.26 | 0.20 | 0.27 | 3.28 |
| Median | 0.70 | 1.29 | 2.92 | 0.34 | 0.51 | 1.76 |

### 5.3.2 Inter-axis coefficients

The coefficients calculated with Equations (5.13), (5.14) and (5.15), representing the consolidated relative sensitivity between directions of vibration at 4 Hz, are reported for each subject and each pair of directions in Table 5.5, together with the median values and similar values derived from previous studies and standards.

## 5.4 Discussion

### 5.4.1 Order effect

By analyzing the results obtained when interchanging the directions of the test and reference, an estimate of the order effect mentioned in Section 5.2.6.3 could be obtained. In particular, it could be determined whether each subject overestimated or underestimated the discomfort caused by the test vibration compared to the reference vibration. Results of that analysis are reported and discussed in details in Section 9.3.1 of the general discussion in Chapter 9. It was assumed that when exposed to a vibration stimuli pair, subjects provide a magnitude estimate $\psi$ equal to :

Table 5.5: Individual inter-axis coefficients calculated with Equations (5.13), (5.14) and (5.15); global inter-axis coefficients calculated using the median individual equivalence coefficients, and comparison with the recommendations of standards and the results of past studies with seated subjects.

| | $K_3(x,y)$ | $K_3(x,z)$ | $K_3(y,z)$ |
|---|---|---|---|
| Subject 1 | 0.65 | 1.43 | 2.20 |
| Subject 2 | 0.57 | 1.39 | 2.45 |
| Subject 3 | 0.66 | 1.63 | 2.47 |
| Subject 4 | 0.77 | 1.08 | 1.41 |
| Subject 5 | 0.65 | 1.12 | 1.73 |
| Subject 6 | 0.69 | 1.28 | 1.84 |
| Subject 7 | 0.83 | 1.40 | 1.70 |
| Subject 8 | 0.73 | 1.38 | 1.90 |
| Subject 9 | 0.82 | 1.59 | 1.94 |
| Subject 10 | 0.96 | 1.17 | 1.22 |
| Subject 11 | 0.60 | 1.62 | 2.72 |
| Subject 12 | 0.82 | 2.56 | 3.14 |
| Global (from median equivalence coefficients) | 0.7 | 1.94 | 2.77 |
| Standard recommendation | 1.00 | 1.74 | 1.74 |
| Griefahn and Bröde (1997) | / | 0.90 | 0.90 |
| Griffin *et al.* (1982a) | 0.61 | 0.84 | 1.38 |

$$\psi = \epsilon \cdot \psi_0 \tag{5.16}$$

where $\psi_0$ is the 'true' value, and $\epsilon$ is a bias coefficient, which may be different from one subject to another, and may depend on the direction of the test vibration but was assumed to be independent on the direction of the reference vibration.

The values of $\epsilon$ were estimated for each subject and in each direction of test stimuli. The procedure and the detailed results are reported in Chapter 9. Some subjects underestimated the discomfort ($\epsilon < 1$), and some subjects overestimated the discomfort ($\epsilon > 1$). The median value of $\epsilon$ was 0.97, and the $25^{\text{th}}$ and $75^{\text{th}}$ percentile were respectively 0.88 and 1.06, so most values were close to 1.

The 36 values of $\epsilon$ obtained for the twelve subjects in the three directions, or the 12 values obtained in either of the three directions were not significantly different from 1 ($p > 0.18$, Wilcoxon) so it was assumed that although an order effect was observed, it would not affect the average results, due to the balance between subjects underestimating the discomfort and subjects overestimating it.

### 5.4.2 Repeatability

Each test stimulus was presented twice during a session, so by comparing the estimates obtained at the first and the second presentation of each test stimulus, the repeatability of the measurement was investigated. The results are reported and discussed in details in Section 9.3.2 of the general discussion in Chapter 9. Subjects tended to give higher ratings to test stimuli on the second presentation. This trend was observed in particular for three of the twelve subjects, for which a statistically significant difference was observed ($p < 0.05$, Wilcoxon). The ratios of the estimates obtained at the second presentation by the estimates obtained at the first presentation were calculated. The median value of this ratio was equal to 1.00 for 8 of the subjects, and was between 1.00 and 1.16 for the 4 remaining subjects.

It was concluded that magnitude estimates probably tend to increase with time during a session. However, because of the randomization of the order of the stimuli in all experiments (which is therefore proved to be necessary), this effect will not affect the results after regressions or other averaging methods are performed.

### 5.4.3 Magnitude-dependence

The coefficients indicating the equivalence between axes were obtained for specific vibration magnitudes. If the rate of growth of sensation n in Steven's power law (Equation 5.1) is different in different directions, then the relative sensitivity between directions will vary with the magnitude of excitation. If subjects are presented a reference stimulus in the fore-and-aft direction with magnitude $a_{x,ref}$, and the equivalent magnitude for a lateral vibration is $a_{y,eq}$, then the equivalence coefficient that will be derived is:

$$K_1(x, y) = \frac{a_{x,ref}}{a_{y,eq}} \tag{5.17}$$

Because the discomfort caused by the two motions is equivalent, and as predicted by Stevens' power law:

$$k_x(a_{x,ref})^{n_x} = k_y(a_{y,eq})^{n_y} \tag{5.18}$$

If Equation (5.18) is multiplied by $2^{n_x}$:

$$k_x(2a_{x,ref})^{n_x} = 2^{n_x} k_y(a_{y,eq})^{n_y} \tag{5.19}$$

$$\Leftrightarrow k_x(2a_{x,ref})^{n_x} = k_y\left(2^{\frac{n_x}{n_y}} a_{y,eq}\right)^{n_y} \tag{5.20}$$

Equation (5.20) implies that a motion of magnitude $2^{\frac{n_x}{n_y}} a_{y,eq}$ in the lateral direction is equivalent to a motion of magnitude $2a_{x,ref}$ in the fore-and-aft direction. That also implies that if the equivalence coefficient had been calculated with a reference magnitude twice as high as the one used to calculate the equivalence coefficient in Equation (5.17), the value of this coefficient would have been, instead of the one found in Equation (5.17) $K(x, y)$:

$$K'(x,y) = \frac{2a_{x,ref}}{2^{\frac{n_x}{n_y}} a_{y,eq}} = 2^{1-\frac{n_x}{n_y}} \frac{a_{x,ref}}{a_{y,eq}} = 2^{1-\frac{n_x}{n_y}} K(x,y) \tag{5.21}$$

This means that doubling the magnitudes of the motions resulted in multiplying the equivalence coefficient by a factor of $2^{1-\frac{n_x}{n_y}}$. This proves that if $n_x = n_y$, the equivalence coefficients do not depend on the magnitude. On the other hand, if there is a difference of 10% between $n_x$ and $n_y$, then doubling the magnitudes will result in having the equivalence coefficients multiplied by $2^{0.1} = 1.07$. It is therefore relevant to determine whether the rates of growth of sensation are identical in all three directions.

The rates of growth of sensation $n$ have been calculated for 16 subjects exposed to 4-Hz fore-and-aft, lateral and vertical vibration in Chapter 4. They are presented in Table 5.6 with the median values.

Table 5.6: Rate of growth $n$ in Stevens' power law for subjects exposed to 4-Hz vibration in the fore-and-aft, lateral and vertical vibration. These results were obtained in Chapter 4.

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| Subject 1 | 1.15 | 1.14 | 1.43 |
| Subject 2 | 0.17 | 0.37 | 0.22 |
| Subject 3 | 0.63 | 0.39 | 1.35 |
| Subject 4 | 0.88 | 1.08 | 0.64 |
| Subject 5 | 0.49 | 0.86 | 0.77 |
| Subject 6 | 0.84 | 0.54 | 0.71 |
| Subject 7 | 0.26 | 0.32 | 0.96 |
| Subject 8 | 0.44 | 0.34 | 0.43 |
| Subject 9 | 0.62 | 1.42 | 1.94 |
| Subject 10 | 0.91 | 0.43 | 1.09 |
| Subject 11 | 0.68 | 0.35 | 0.92 |
| Subject 12 | 1.18 | 0.65 | 0.9 |
| Subject 13 | 0.89 | 1.09 | 0.83 |
| Subject 14 | 0.57 | 1.66 | 0.78 |
| Subject 15 | 0.97 | 0.62 | 0.42 |
| Subject 16 | 0.62 | 0.52 | 0.48 |
| Median | 0.65 | 0.58 | 0.81 |

The exponents $n$ at 4 Hz were not significantly different from one direction to another (fore-and-aft and lateral: $p = 0.72$, Wilcoxon; fore-and-aft and vertical: $p = 0.17$, Wilcoxon;

lateral and vertical: $p = 0.20$, Wilcoxon). So, although the median values appear different, the experimental data are not sufficiently powerful to conclude that the ratio of sensitivity to 4-Hz vibration between directions does vary significantly with the magnitude of the vibration.

### 5.4.4 Inter-axis coefficients

Standards ISO 2631-1 (1997) and BS 6841 (1987) advocate the use of frequency weightings $W_b$ and $W_d$ for evaluating vertical and horizontal and vibration, respectively. Multiplying coefficients equal to 1.0 are to be used for all translation axes, so the assumed relative sensitivity at 4 Hz is:

$$\frac{W_y}{W_x} = \frac{W_d(4\text{Hz})}{W_d(4\text{Hz})} = 1 \tag{5.22}$$

$$\frac{W_z}{W_x} = \frac{W_b(4\text{Hz})}{W_d(4\text{Hz})} = \frac{0.889}{0.512} = 1.736 \tag{5.23}$$

$$\frac{W_z}{W_y} = \frac{W_b(4\text{Hz})}{W_d(4\text{Hz})} = \frac{0.889}{0.512} = 1.736 \tag{5.24}$$

These values are compared with experimental values in Table 5.5.

Griefahn and Bröde (1997) investigated the subjective equivalence between lateral and vertical vibration for seated people, and compared it with the relation predicted by the standards. Subjects were exposed to a vertical sinusoidal reference vibration, followed by a lateral sinusoidal test vibration, and they were asked to adjust the magnitude of the test vibration until it caused “equal sensation as the reference”, and the adjusted magnitude was compared with the prediction of standard obtained by multiplying the magnitude of the reference by the ratio of frequency weightings $W_k/W_d$. The difference between expected and adjusted magnitudes was reported; however, the ratio of the adjusted to the expected magnitudes (or difference in dB) is more of interest. The adjusted magnitude was, on average, 7 dB lower than the expected magnitude at 3.15 Hz, and 4 dB lower at 6.3 Hz. Over all frequencies tested (from 1.6 to 12.5 Hz), the difference was, on average, around -6 dB. This suggests that standards overestimate the discomfort caused by vertical vibration compared to horizontal vibration (or underestimate the discomfort caused by horizontal vibration compared to vertical vibration). The results were similar if $W_b$ was used instead of $W_k$. This means that the adjusted magnitude was in general half of the expected magnitude, suggesting that the frequency weighting $W_d$ should be multiplied by a factor of 2 in order to reflect the actual inter-axis equivalence. This would correspond to an inter-axis coefficient of about:

$$\frac{W_z}{W_y} = 0.9 \tag{5.25}$$

The same procedure was used with fore-and-aft test vibration instead of lateral vibration. The results were similar, with adjusted magnitudes about 6 dB lower than the expected magnitudes.

Griffin *et al.* (1982a) constructed equivalent sensation contours for seated people exposed to fore-and-aft, lateral, and vertical vibration, using a common vertical reference. This enables the comparison of sensitivity between directions. Relative sensitivity was derived from the comfort contours, and in particular at 4 Hz:

$$\frac{W_y}{W_x} = 0.61 \tag{5.26}$$

$$\frac{W_z}{W_x} = 0.84 \tag{5.27}$$

$$\frac{W_z}{W_y} = 1.38 \tag{5.28}$$

The studies of Griffin *et al.* (1982a) and Griefahn and Bröde (1997) show differences: whereas Griffin *et al.* (1982a) found subjects more sensitive to fore-and-aft vibration than lateral vibration ($K_y/K_x = 1.64$), Griefahn and Bröde found similar sensitivity in the fore-and-aft and lateral directions. The difference might be due to differing transmission of vibration to the body in the two studies associated with differing postures, differences in the vibration at the feet, differences in the postural support from the feet, differences in the contour and friction at the seat surface.

Seated people were more sensitive to fore-and-aft vibration than to lateral vibration at 4 Hz and at frequencies up to 5 Hz (Griffin *et al.*, 1982a). The same observation was made with standing people in the present study: individual values of $K_y/K_x$ were less than 1.0, and the inter-axis equivalence calculated with the median equivalence coefficients was 0.7. The increased sensitivity to fore-and-aft vibration may be due to the effects of vibration on the postural stability of standing people over this frequency range (Thuong and Griffin, 2011b), with stability threatened more by fore-and-aft vibration than by lateral vibration.

Standing people exposed to 4-Hz vibration in the present study, were more sensitive to vertical vibration than to horizontal vibration, like the seated subjects of Griffin *et al.* (1982a), but unlike those of Griefahn and Bröde (1997). For both seated and standing people, the standards provide Kz/Ky values greater than 1.0, suggesting seated and standing people are more sensitive to 4-Hz vertical vibration than to 4-Hz horizontal vibration. This is consistent with the results by Griffin *et al.* (1982a) and the present results, although the standard seems to underestimate the sensitivity to vertical vibration of both standing and seated subjects.

It seems reasonable to assume that the direction of 4-Hz vibration has different effects on standing and seated people. Although the standards suggest similar magnitudes of fore-and-aft and lateral vibration will cause similar discomfort, the results show that standing people are more sensitive to 4-Hz fore-and-aft vibration than to 4-Hz lateral vibration. Similarly, relative to the discomfort caused by horizontal vibration, vertical vibration at 4 Hz causes more discomfort in standing people than in seated people.

### 5.4.5 Multi-axis frequency weightings

Frequency weightings were determined in Chapter 4 for standing people exposed to fore-and-aft, lateral, and vertical vibration, which can be used to compare the discomfort caused by vibrations at different frequencies. However, as the study did not include inter-axis comparisons, the weightings cannot be used to compare vibration in different directions. This can be made possible by adjusting the frequency weightings obtained in Chapter 4 so that the ratio of the weightings at 4 Hz corresponds to the inter-axis coefficients determined here (Table 5.5). To achieve this equality, the weighting for vertical vibration was arbitrarily chosen to remain unchanged, because it shows many similarities with the weighting recommended in the standard ($W_b$). The weightings fore fore-and-aft and lateral vibration were multiplied by 2.09 and 1.80 respectively.The multi-axis frequency weightings obtained with this method are shown in Table 5.7 and Figure 5.3.

Analog filters were constructed reflecting the weightings. For horizontal vibration, results suggest that standing people are more sensitive to fore-and-aft vibration than to lateral vibration at lower frequencies, but that the sensitivity is approximately equivalent at higher frequencies. This may be due to greater instability when subjects are exposed to fore-and-aft vibration than to lateral vibration (such instability only occurs at frequencies less than 3 or 4 Hz). To reflect the results, the frequency weighting for fore-and-aft and lateral vibration were represented with similar filters, that correspond (asymptotically) to constant velocity at low frequencies and constant acceleration at high frequencies; however the transition frequency was chosen at 3.15 Hz for lateral vibration and 4 Hz for fore-and-aft vibration. This makes the weighting for fore-and-aft vibration greater at lower frequencies, with the difference decreasing at frequencies greater than about 3 Hz. The proposed filters are compared with the experimental weightings in Figure 5.4.

It is interesting to note that, according to the study reported in Chapter 4, postural instability is a cause of discomfort at frequencies up to 4 Hz for fore-and-aft vibration, but only up to 2.5 Hz for lateral vibration (Figure 4.11). Those frequencies are similar to the transition frequencies proposed for the filters, suggesting that they represent the boundary between two frequency domains where mechanisms of discomfort are different.

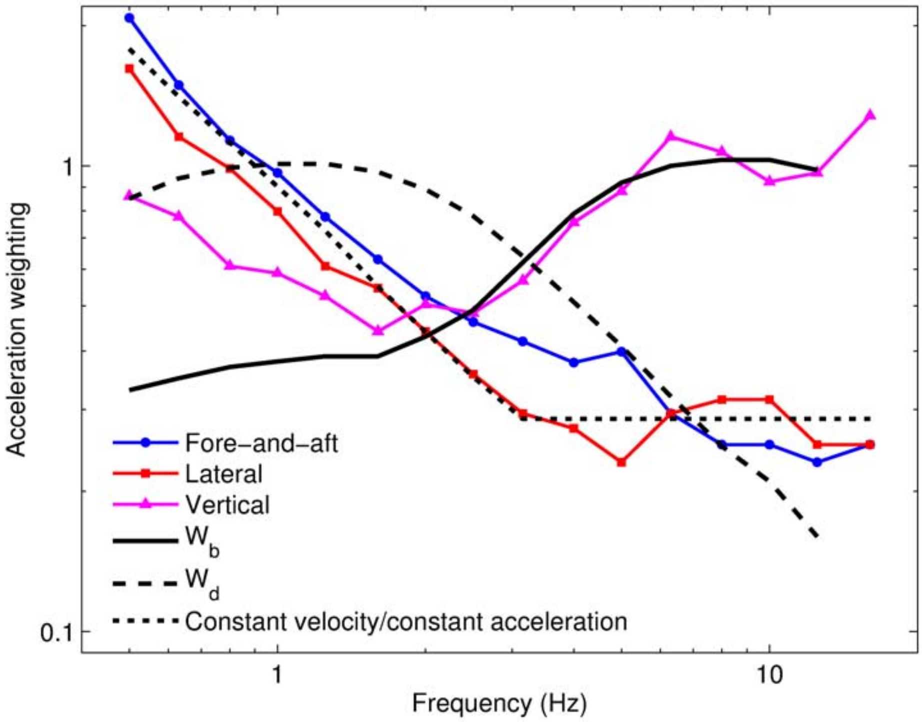


Figure 5.3: Frequency weightings obtained in Chapter 4 and adjusted in the view of the present results, compared with standard weightings.

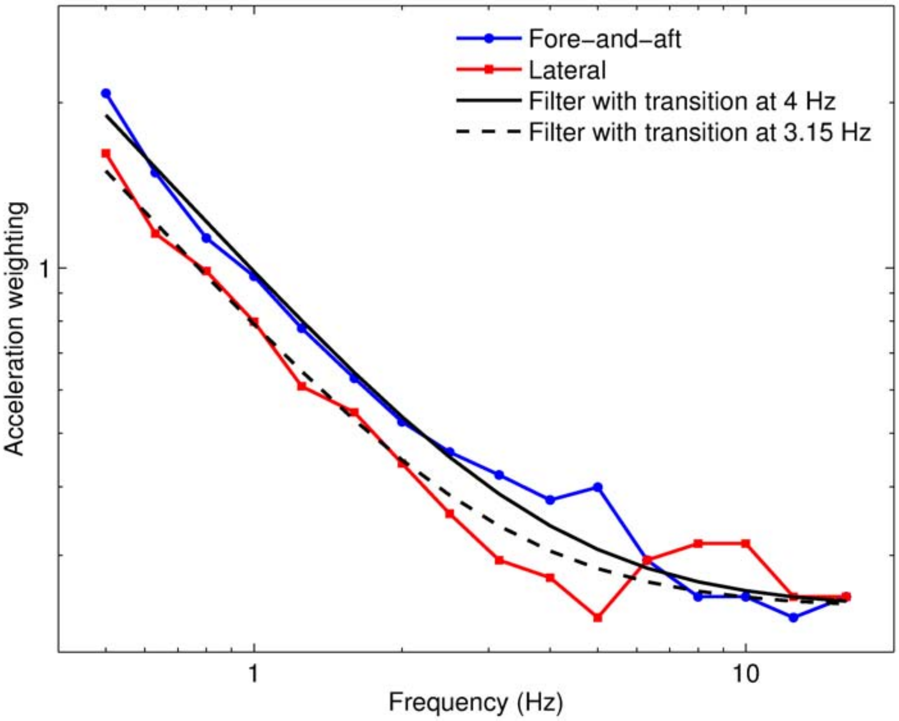


Figure 5.4: Frequency weightings obtained in Chapter 4 and adjusted in the view of the present results, compared with proposed weightings. The two lines without markers represent analog filters asymptotically equal to constant velocity at lower frequencies and constant acceleration at higher frequencies; the transition frequency is indicated for each line.

Table 5.7: Frequency weightings obtained by adjusting the weightings obtained in Chapter 4 using the cross-axis coefficients obtained in the present experiment. Weightings were also multiplied by an arbitrary constant so that the weighting for vertical vibration matches $W_b$.

| Frequency (Hz) | Fore-and-aft vibration | Lateral vibration | Vertical vibration |
|---|---|---|---|
| 0.5 | 2.079 | 1.617 | 0.861 |
| 0.63 | 1.491 | 1.155 | 0.777 |
| 0.8 | 1.134 | 0.987 | 0.609 |
| 1 | 0.966 | 0.798 | 0.588 |
| 1.25 | 0.777 | 0.609 | 0.525 |
| 1.6 | 0.63 | 0.546 | 0.441 |
| 2 | 0.525 | 0.441 | 0.504 |
| 2.5 | 0.462 | 0.357 | 0.483 |
| 3.15 | 0.42 | 0.294 | 0.567 |
| 4 | 0.378 | 0.273 | 0.756 |
| 5 | 0.399 | 0.231 | 0.882 |
| 6.3 | 0.294 | 0.294 | 1.155 |
| 8 | 0.252 | 0.315 | 1.071 |
| 10 | 0.252 | 0.315 | 0.924 |
| 12.5 | 0.231 | 0.252 | 0.966 |
| 16 | 0.252 | 0.252 | 1.281 |

For evaluating vertical vibration, a weighting has been suggested in Chapter 4 which is derived from the standard weighting $W_b$. The weighting curve $W_b$ was multiplied by a filter similar to those proposed for horizontal vibration, but with a transition frequency at 1 Hz. The resulting weightings for all directions are summarized in Figure 5.5.

## 5.5 Conclusion

The effect of direction on the discomfort of standing people exposed to 4-Hz vibration was found to be different from the predictions of standards and the results found in literature. Comparisons suggest that this difference is due to the difference in posture between the present study (standing people) and the studies in the literature and the standards (seated people). For example, it has been observed that standing people are more sensitive to fore-and-aft vibration than lateral vibration at 4 Hz, and, in view of the results of Chapter 4, at frequencies below 4 Hz. This is probably due to the occurrence of postural instability, which is experienced by subjects at these frequencies when exposed to fore-and-aft vibration and, to a lesser extent, lateral vibration. Standards also seem to underestimate the discomfort caused by vertical vibration at 4 Hz compared to horizontal vibration.

Based on the results of Chapter 4, frequency weightings constructed with the help of analog filters were suggested for each direction, which take account of the relative sensitivity to

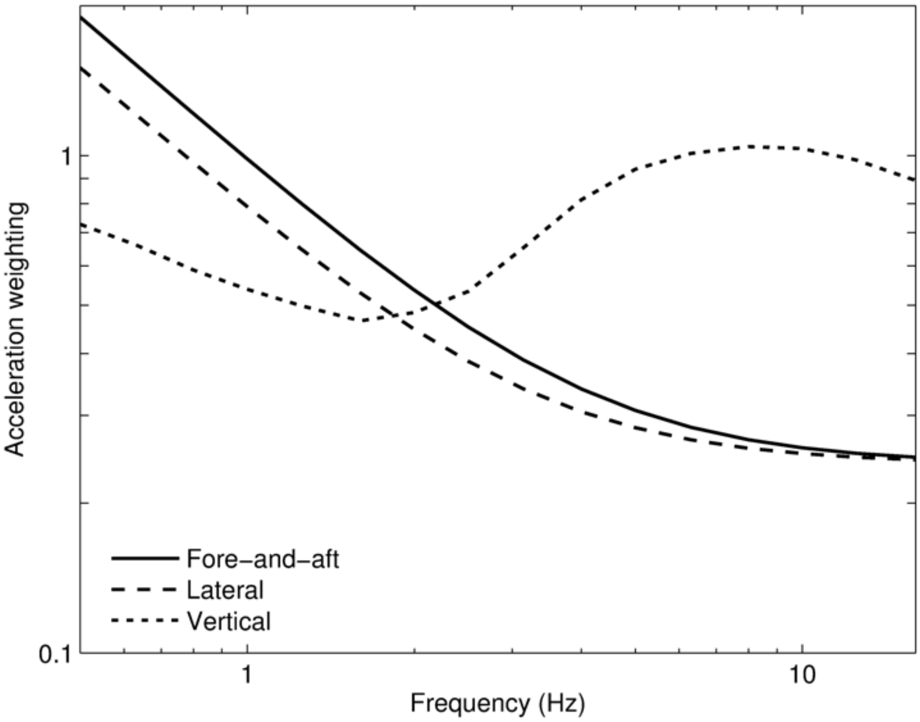


Figure 5.5: Proposed weightings for evaluating vibration in all three directions.

vibration between directions at 4 Hz. They will be integrated in a general model of the vibration discomfort of standing people.

# Chapter 6

# The effect of postural supports

## 6.1 Introduction

It was shown in Chapter 4 that the sensitivity of standing people to vibration acceleration depends on the vibration frequency. The frequency-dependence was found to be consistent with the recommendations of standards for vertical vibration, but not for horizontal vibration. Frequency weightings have been produced that can be used for evaluating vibration discomfort of standing people in trains. However, train passengers rarely stand without using any support. They often hold or lean against a structure, either to assist stability while exposed to motion or to relieve muscles used when standing unsupported. In such situations, the frequency-dependence might be modified. This has not been investigated in the past, and it is therefore relevant to discover whether, and to what extent, and how, postural supports affect the discomfort caused by the vibration of standing passengers. From a practical point of view, this knowledge is necessary for evaluating the discomfort of passengers standing in several common postures. It is also useful in order to improve understanding of the mechanisms of vibration discomfort of standing people, and to ensure the applicability to real situations of studies conducted with subjects standing without any support.

Contact with parts of a train may be expected to modify the motion of the bodies of passengers and their comfort. For seated people, a backrest tends to increase the transmission of lateral and fore-and-aft vibration to the head (Paddan and Griffin, 1988b). The discomfort caused by vibration tends to be reduced by the use of a backrest when exposed to fore-and-aft vibration at frequencies in the range 0.2 to 2 Hz (Wyllie and Griffin, 2009), but increased by a backrest when exposed to fore-and-aft vibration at frequencies greater than 4 Hz (Parsons *et al.*, 1982), or exposed to lateral vibration at frequencies greater than 0.315 Hz (Parsons *et al.*, 1982; Wyllie and Griffin, 2007). It seems reasonable to expect that any effect of supports on the vibration discomfort of standing people will also depend on the frequency and the direction of the vibration. Designers may use current standards to predict the vibration discomfort of passengers who stand without holding or leaning on a support, but they have no means of anticipating discomfort when the passengers are supported. Knowledge of the effects of supports on vibration discomfort may assist the design of transport and also assist researchers seeking to improve understanding of the mechanisms involved in vibration discomfort.

This study was designed to determine and understand how postural supports similar to those used in trains influence the discomfort caused by horizontal vibration over the range of frequencies that may be experienced by passengers standing in trains. It was hypothesised that postural supports would improve the comfort of standing people exposed to fore-and-aft or lateral vibration at the lowest frequencies, where vibration can cause loss of balance (Chapter 4), but degrade it at higher frequencies.

This study has been partly reported by Thuong and Griffin (2011a).

## 6.2 Method

### 6.2.1 Motions

All vibration stimuli were sinusoidal and 6 seconds in duration, including a 1-second cosine-tapered start and a 1-second cosine-tapered end. Subjects were exposed to pairs of motions: a ‘reference vibration’ followed by a ‘test vibration’ in the same direction (i.e. either fore-and-aft or lateral).

The reference stimuli had a frequency of 2 Hz and a magnitude of 0.5 $m.s^{-2}$ r.m.s. in the same axis as the test motion, presented either with postural support (‘within condition’ experiment, Section 6.2.3.2) or without a support (‘between conditions’ experiment, Section 6.2.3.3).

With both fore-and-aft and lateral vibration, the ‘test stimuli’ were presented at the six preferred octave centre frequencies: 0.5, 1.0, 2.0, 4.0, 8.0, and 16 Hz. At each frequency, the test stimuli were presented at five magnitudes, in steps of 4 dB (Figure 6.1 and Table 6.1). From preliminary studies, the magnitudes were chosen so that they would cause approxilmately equivalent discomfort at all frequencies. They had the same acceleration at frequencies from 2 to 8 Hz and the same velocity at frequencies less than 2 Hz and greater than 8 Hz.

The motions were produced using a hydraulic horizontal vibrator capable of 1-metre displacement. Fore-and-aft or lateral vibration was obtained by orientating subjects relative to the axis of motion. The motion stimuli were generated using HVLab software (version 3.81) with a sampling rate of 1000 samples per second. The acceleration of the platform was monitored using piezoresistive accelerometers (Entran Model EGCSY-240D*-10) and

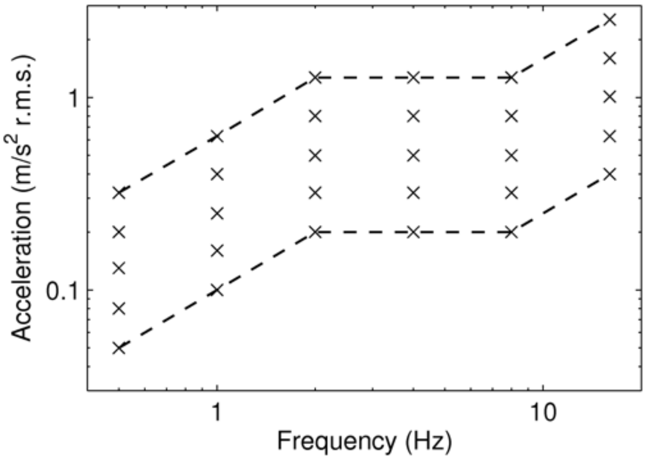


Figure 6.1: Frequencies and magnitudes of the vibration stimuli used in the experiment.

Table 6.1: Frequencies and magnitudes of the vibration stimuli used in the experiment.

| Frequency | Magnitudes (m.s$^{-2}$ r.m.s.) | | | | |
|---|---|---|---|---|---|
| 0.5 Hz | 0.05 | 0.08 | 0.13 | 0.2 | 0.32 |
| 1 Hz | 0.1 | 0.16 | 0.25 | 0.4 | 0.63 |
| 2 Hz | 0.2 | 0.32 | 0.5 | 0.8 | 1.27 |
| 4 Hz | 0.2 | 0.32 | 0.5 | 0.8 | 1.27 |
| 8 Hz | 0.2 | 0.32 | 0.5 | 0.8 | 1.27 |
| 16 Hz | 0.4 | 0.63 | 1.01 | 1.6 | 2.54 |

an HVLab data acquisition system. The acceleration was sampled at 1000 samples per second, after low-pass filtering at 40 Hz.

The simulators and their performances are described in Section 3.2.1 of Chapter 3.

### 6.2.2 Postural support

Subjects stood in four postures (Figure 6.2). Except with the shoulder support, where feet were side-by-side, the distance between the feet was such that the distance between the outer edges of the feet was approximately equal to 350 mm, the median shoulder breadth (Pheasant, 1988).

i. 'free': a normal erect posture.

ii. 'bar': identical to the 'free' posture, except the subjects held a vertical bar with their right hand at shoulder height and the elbow unlocked.

iii. 'shoulder': the mid-sagittal plane was parallel to the support wall, with the right shoulder resting against the wall. The feet were parallel and side by side, placed

280 mm away from the wall, and the body was straight, producing an angle of about 6 degrees to the vertical.

iv. 'backrest': subjects rested their buttock against a rigid board, the rest of the back being free of support. The distance between the wall and the feet was 200 mm. This means that the legs produced an angle of about 13 degrees with the vertical. The back was straight and vertical.

Figure 6.2: Postures adopted by the subjects: (i) free; (ii) bar; (iii) shoulder; (iv) back.

The three supports were attached to an extruded aluminium frame secured to the 150 cm by 100 cm table of the vibrator. The 'bar' support consisted of a vertical bar (diameter 45 mm) that was part of the aluminium framework. The supports of the 'shoulder' and 'backrest' were provided by plywood boards (1/4-inch thick) screwed to the aluminium framework.

Acceleration was measured at each support, and the ratio of the acceleration to the acceleration of the vibrator platform in the direction of motion was calculated for all motions employed in the study. In the direction of motion, this ratio was between 0.9 and 1.1, except at 16 Hz where it varied between 1.1 and 1.4 for the back support, and between 1.2 and 1.4 for the shoulder support, depending on the vibration magnitude. For supports perpendicular to the direction of motion of the platform (i.e. in the cross-axis), the ratio between motion of the support and motion of the platform was less than 0.1, except at 16 Hz where it was between 0.2 and 0.3 for the shoulder support, and between 0.1 and 0.2 for the back support, depending on the vibration magnitude.

### 6.2.3 Procedure

#### 6.2.3.1 General procedure

In all postures, subjects were instructed to:

- Place their feet on marks on the floor (the base of support was 35-mm wide, except for the shoulder posture where the feet were together)
- Try to keep the weight equally distributed between the feet
- Maintain the knees locked (avoiding bending legs to reduce the transmission of vibration)
- Allow the arms to hang freely (except when holding the bar).
- Look straight ahead

The method of magnitude estimation (described in Section 3.4.1) was employed to determine the discomfort caused by each of the test motions relative to the discomfort caused by a reference motion having a frequency of 2 Hz and a magnitude of 0.5 m.s$^{-2}$ r.m.s. in the same axis as the test motion, presented either with postural support (‘within condition’ experiment, Section 6.2.3.2) or without a support (‘between conditions’ experiment, Section 6.2.3.3).

The subjects attended two sessions in which they were exposed to either fore-and-aft or lateral vibration: half of the subjects were first exposed to fore-and-aft vibration and half of the subjects began with lateral vibration. During each session, the four supports were presented in random orders.

For each condition (i.e., each support and each direction of vibration), a ‘within conditions’ study and a ‘between conditions’ study were performed (except for the ‘free posture’).

#### 6.2.3.2 Within conditions - effects of the frequency and magnitude of vibration

For both directions of motion and all postures, subjects were exposed to the reference motion (2 Hz at 0.5 $m.s^{-2}$ r.m.s.), followed by a test motion (at a randomly chosen frequency and magnitude from the range shown in Figure 6.1 and Table 6.1). For the test and the reference motions, the subjects were using the same postural support. After the presentation of the test motion, subjects were asked to provide a number reflecting the discomfort it caused, assuming the discomfort caused by the reference motion was 100. The subjects could ask for the pair of motions to be repeated if they were not sure. Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli (Appendix A.3.1). This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli.

#### 6.2.3.3 Between conditions - effects of postural support

The procedure was identical to the 'within condition' part of the study, except that the reference motion was received with the subjects standing in the 'free posture' and exposed to a 2-Hz vibration at a magnitude of 0.5 $m.s^{-2}$ r.m.s., called the 'absolute reference'. After experiencing this reference motion, the subjects changed posture before receiving a test stimulus. With each support, the test stimuli were presented at five magnitudes of 2 Hz vibration in the same direction as the reference motion.

#### 6.2.3.4 Localization of discomfort

Subjects were also exposed to single motions, and asked in which parts of the body the vibration felt most uncomfortable, using numbers indicated on a bodymap presented to them (Figure 6.3, Appendix A.3.2). This was repeated for each support condition, at the middle magnitude (third magnitude in Table 6.1 and Figure 6.1) of each of the six frequencies of interest.

### 6.2.4 Subjects

Twelve healthy male university students and staff with median age 28 years (range 21 to 38 y), stature 177 cm (159 to 192 cm), weight 74 kg (56 to 90 kg) participated in the study. The physical characteristics of the subjects are reported in Table 6.2. Subjects attended two sessions (one for each direction of motion), each lasting 60 minutes.

The subjects wore socks but not shoes and wore a loose harness in case they should fall (Figure 6.2). The harness did not provide support or restrict movement when subjects stood as instructed. They wore headphones delivering broadband noise at 65 dB(A).

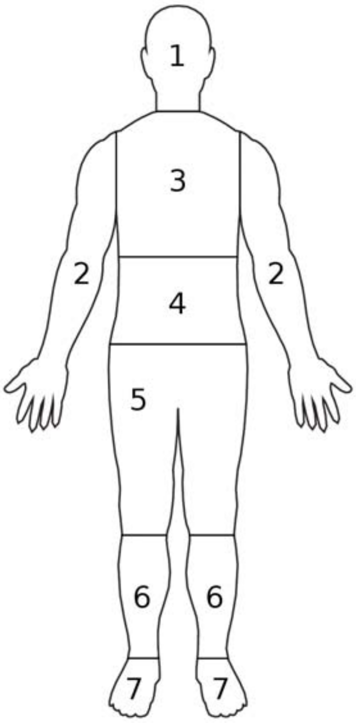


Figure 6.3: Body map used in the experiment.

Table 6.2: Physical characteristics of the subjects used in the experiment.

| Subject | Gender | Age | Height (cm) | Weight (kg) | Handedness |
|---|---|---|---|---|---|
| 1 | M | 28 | 159 | 63 | R |
| 2 | M | 21 | 178 | 67 | R |
| 3 | M | 30 | 170 | 56 | R |
| 4 | M | 28 | 171 | 84 | R |
| 5 | M | 38 | 170 | 83 | R |
| 6 | M | 27 | 177 | 68 | R |
| 7 | M | 28 | 178 | 86 | R |
| 8 | M | 26 | 178 | 74 | R |
| 9 | M | 22 | 171 | 73 | R |
| 10 | M | 32 | 176 | 79 | R |
| 11 | M | 31 | 178 | 64 | R |
| 12 | M | 23 | 192 | 90 | R |

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

### 6.2.5 Analysis

The method used to produce equivalent sensation contours, based on magnitude estimation (Section 3.4.2) and Stevens' power law, is identical to that used in Chapter 4. Stevens' power law (Stevens, 1975) was used to relate the magnitude estimates of subject discomfort, $\psi$, to the physical magnitudes of the motions, $\varphi$:

$$\psi = k\varphi^n \tag{6.1}$$

where $k$ (the 'constant' in Stevens' power law) and $n$ (the 'exponent') are assumed to be constant at any frequency. With both whole-body vibration of seated persons and hand-transmitted vibration, the exponent depends on the frequency of vibration (Morioka and Griffin, 2006a and 2006b; Wyllie and Griffin, 2007 and 2009).

Values of the exponent, $n$, at each frequency were determined by regression between the logarithms of the magnitude estimates and the vibration acceleration using bisquare weights to reduce bias from outlier values (as explained in Section 3.4.3):

$$\log(\psi) = \log(k) + n\log(\varphi) \tag{6.2}$$

For each individual, equivalent comfort contours were obtained for different values of discomfort, $\psi$, using individual values of $k$ and $n$, assuming $k$ and $n$ depend on frequency:

$$\varphi(f) = \left[\frac{\psi}{k(f)}\right]^{\frac{1}{n(f)}} \tag{6.3}$$

This equation gives the acceleration, $\varphi(f)$, needed at each frequency to achieve a given level of discomfort, $\psi$.

Two types of frequency weighting were constructed. Weightings showing the frequency-dependence of sensitivity to acceleration with each support were derived by inverting the equivalent comfort contours and normalizing them to have the same weighting at 0.5 Hz. Additionally, the inverses of the ratios between the comfort contours obtained with and without supports, referred to as 'support weightings', were calculated to show how vibration discomfort was affected by each support. A support weighting of 2.0, for example, means the discomfort experienced when holding the support would be similar to the discomfort when not holding the support but exposed to double the magnitude of vibration. So, a weighting greater than 1.0 indicates that the support increases discomfort, and a weighting less than 1.0 indiates the the discomfort is reduced. The support weightings therefore show the frequency-dependent effects of each support on vibration discomfort and can be used to take account of the effect of a support when evaluating vibration.

Non-parametric tests (the Friedman two-way analysis of variance by ranks, the Wilcoxon matched-pairs signed ranks test, and the Spearman rank-order correlation coefficient) were employed in the statistical analysis.

The procedure used for the data analysis is summarized in Figure 6.4.

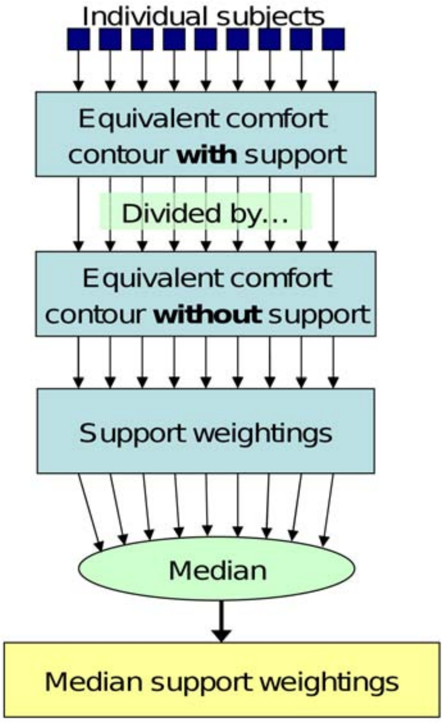


Figure 6.4: Summary of the data analysis procedure.

## 6.3 Results

### 6.3.1 Growth of sensation

The median values of the constant ($k$) and the exponent ($n$) in Stevens' power law, used to construct equivalent sensation contours and frequency weightings are reported in Tables 6.3 and 6.4 for fore-and-aft and lateral vibration respectively.

Table 6.3: Median values of the constant ($k$) and exponent ($n$) in Stevens' power law, at difference frequency of fore-and-aft vibration and for different support conditions.

| Frequency (Hz) | $k$ | | | | $n$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Free | Bar | Shoulder | Back | Free | Bar | Shoulder | Back |
| 0.5 | 821 | 647 | 1331 | 489 | 1.50 | 1.25 | 1.54 | 1.24 |
| 1 | 323 | 383 | 330 | 465 | 1.20 | 1.39 | 1.27 | 1.36 |
| 2 | 169 | 180 | 203 | 259 | 1.00 | 0.92 | 0.90 | 0.92 |
| 4 | 167 | 186 | 155 | 257 | 1.34 | 1.06 | 1.12 | 0.56 |
| 8 | 109 | 149 | 117 | 218 | 1.00 | 0.92 | 1.04 | 0.81 |
| 16 | 71 | 103 | 94 | 226 | 1.25 | 0.85 | 1.05 | 0.62 |

Table 6.4: Median values of the constant ($k$) and exponent ($n$) in Stevens' power law, at different frequencies of lateral vibration and for different support conditions.

| Frequency | $k$ | | | | $n$ | | | |
|---|---|---|---|---|---|---|---|---|
| (Hz) | Free | Bar | Shoulder | Back | Free | Bar | Shoulder | Back |
| 0.5 | 964 | 512 | 330 | 410 | 1.49 | 0.98 | 1.00 | 1.04 |
| 1 | 337 | 278 | 466 | 550 | 1.33 | 1.18 | 1.22 | 1.37 |
| 2 | 156 | 148 | 291 | 252 | 1.08 | 1.04 | 0.94 | 0.80 |
| 4 | 128 | 123 | 236 | 195 | 1.43 | 1.09 | 0.93 | 0.84 |
| 8 | 130 | 116 | 208 | 126 | 1.38 | 1.25 | 0.93 | 1.40 |
| 16 | 81 | 88 | 188 | 120 | 1.08 | 0.95 | 0.68 | 0.89 |

### 6.3.2 Equivalent comfort contours

Median equivalent comfort contours corresponding to a magnitude estimate of '100' (i.e. discomfort equivalent to that caused without support when exposed to the reference motion of 2 Hz at 0.5 m.s$^{-2}$ r.m.s. in the same direction as the test motion) for all four support conditions and both fore-and-aft and lateral vibration are shown in Figure 6.5. Conditions where the equivalent comfort contours are significantly different with and without support ($p < 0.05$, Wilcoxon) are marked. The equivalent comfort contours obtained without support are similar in shape to the contours obtained with the same posture in Chapter 4.

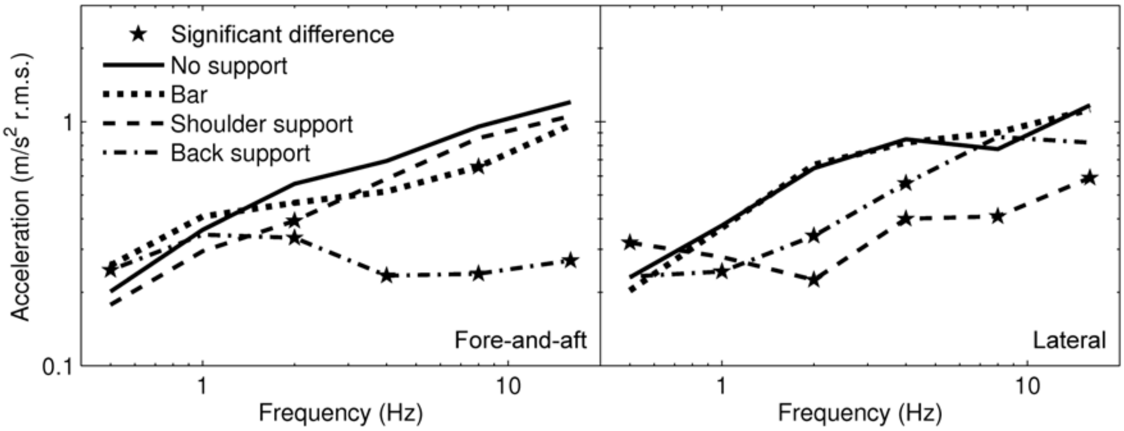


Figure 6.5: Equivalent comfort contours corresponding to a magnitude estimate of '100' (i.e. the discomfort caused by a 2-Hz vibration at 0.5 m.s$^{-2}$ r.m.s. presented without support in the same axis of motion); frequencies where the acceleration on the contour is significantly different with and without support ($p < 0.05$, Wilcoxon) are marked with a star.

### 6.3.3 Effect of postural supports

For each support and at each frequency, support weightings were derived (as described in Section 6.2.5). A support weighting greater than 1.0 means the support increased discomfort (and greater values indicate greater discomfort), while a support weighting less than

1.0 means the support reduced discomfort. The median support weightings are reported in Table 6.5 and are shown with inter-quartile ranges in Figure 6.6. The support weighting for the back support with fore-and-aft vibration at 4, 8, and 16 Hz shows the greatest inter-subject variability, due to some subjects being very sensitive in this condition, including at the lowest vibration magnitudes. The conditions where the contours differ significantly with and without support are indicated in Table 6.5 with a sign, which indicates whether the support increased or decreased discomfort.

Table 6.5: Median support weightings for the contour corresponding to a magnitude estimate of '100' (i.e. the discomfort caused by 2-Hz vibration at 0.5 $m.s^{-2}$ r.m.s. presented without support in the same axis of motion). Conditions where the support had a statistically significant effect ($p < 0.05$, Wilcoxon) on the acceleration contour are marked with a sign: (+) greater acceleration (improved comfort with support); (-) smaller acceleration (degraded comfort with support).

| | | 0.5 Hz | 1 Hz | 2 Hz | 4 Hz | 8 Hz | 16Hz |
|---|---|---|---|---|---|---|---|
| Fore-and-aft | Bar | 0.94 | 0.96 | 1.08 | 1.2 | 1.32(-) | 1.15 |
| | Shoulder | 1.09 | 1.2 | 1.44(-) | 1.2 | 1.13 | 1.06 |
| | Back | 0.92(+) | 0.97 | 1.54(-) | 2.57(-) | 2.98(-) | 2.96(-) |
| Lateral | Bar | 1.06 | 0.98 | 1.04 | 0.99 | 0.99 | 1.28 |
| | Shoulder | 0.77(+) | 1.43 | 3.24(-) | 2.11(-) | 1.82(-) | 2.73(-) |
| | Back | 0.96 | 1.56(-) | 2.28(-) | 1.40(-) | 0.86 | 1.36 |

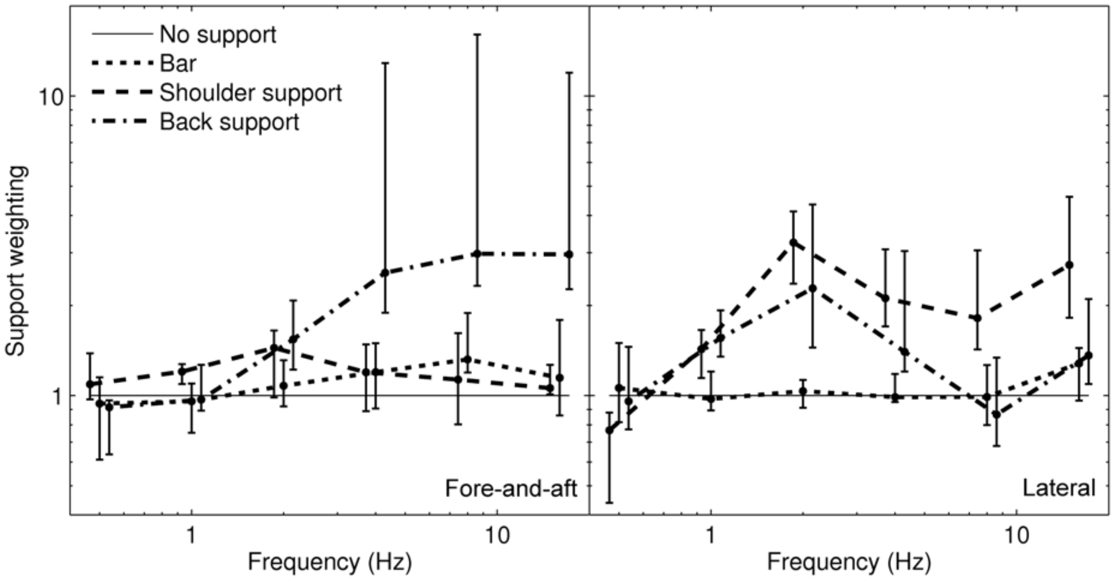


Figure 6.6: Median 'support weightings' and inter-quartile ranges with fore-and-aft and lateral vibration and the four support conditions (for data, see Appendix E.5, Table E.7).

In two conditions with 0.5-Hz vibration (the back support with fore-and-aft vibration and the shoulder support with lateral vibration), the use of a support increased the acceleration on the comfort contour, meaning the support significantly reduced discomfort caused by the vibration (conditions marked with '(+)' in Table 6.5). In all other conditions where the support had a statistically significant effect, the use of a support increased the discomfort caused by the vibration (conditions marked with '(-)' in Table 6.5).

### 6.3.4 Localization of discomfort

The areas of the body where subjects felt the most discomfort are shown in Figure 6.7.

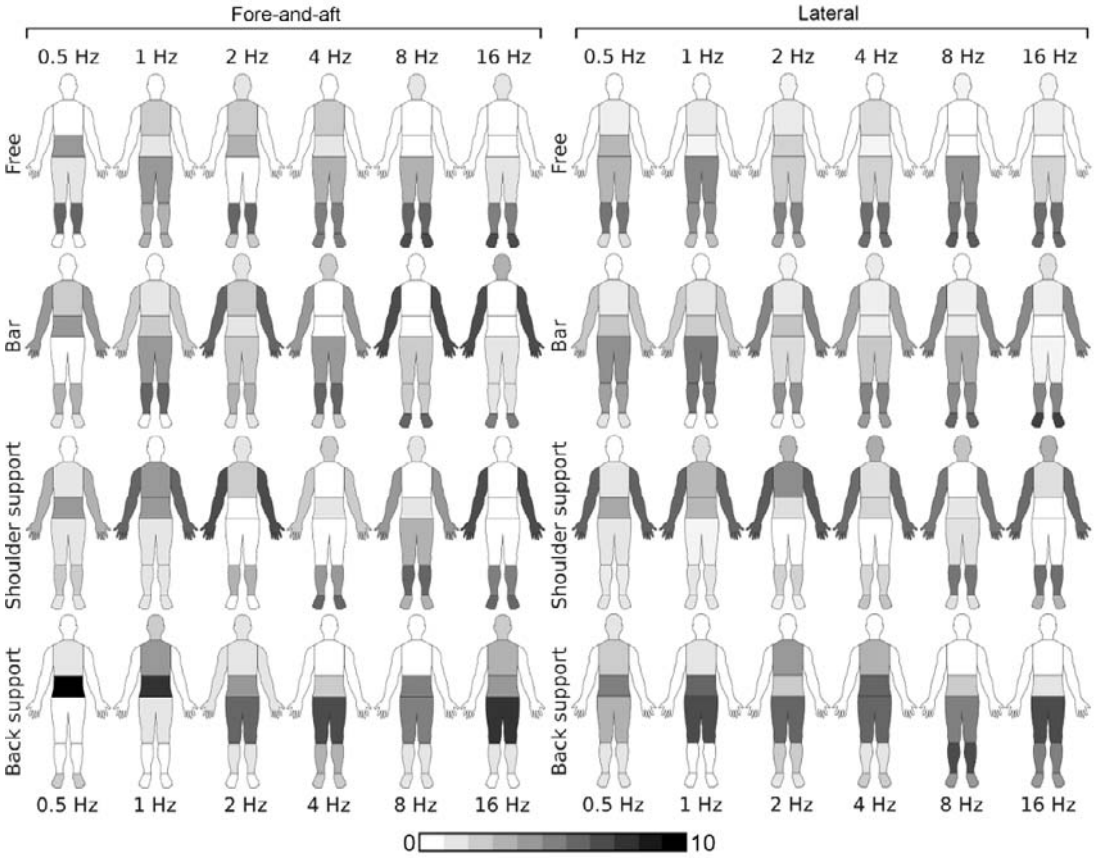


Figure 6.7: Localization of discomfort in the body at each frequency and with each support. The shading indicates the number of subjects who localized the main cause of discomfort in the corresponding body area.

Several observations can be made:

- When no support is being used, the discomfort tends to be located in lower parts of the body as the frequency increases: at the lowest frequencies, vibration in the abdomen causes discomfort, whereas at the highest frequencies, the discomfort is mainly due to vibration of the feet.
- A similar observation can be made when subjects held a bar or used a shoulder support: discomfort shifts from the abdomen and thighs to the feet as frequency increases. However, at high frequencies, in addition to this effect, a great amount of discomfort is also due to vibration in the arms and torso, and in some cases the head.

- When subjects used a back support, discomfort was mainly due to vibration of the abdomen and thighs/buttock (subjects mainly reported vibration at the buttock, but the body map did not distinguish between the two body areas). Vibration at the abdomen seems predominant at lower frequencies (<2 Hz), while vibration in lower parts of the body is predominant at higher frequencies.

## 6.4 Discussion

### 6.4.1 Equivalent sensation contours

The equivalent comfort contours obtained for subjects standing without supports were compared with the contours reported in Chapter 4 (for data, see Appendix E.6, Table E.8). Those contours were obtained in similar conditions, but with a larger sample of subjects (16 subjects), at more frequencies (all preferred third-octave frequencies in the range 0.5 to 16 Hz), and more magnitudes at each frequency. The visual field was also different, as subjects could see outside the cabin in the present experiment, but not in the study reported in Chapter 4 (see Section 3.3.3). The contours obtained in both studies are shown in Figure 6.8 with the acceleration ranges (because the choice of magnitude ranges may influence the shape of the contours).

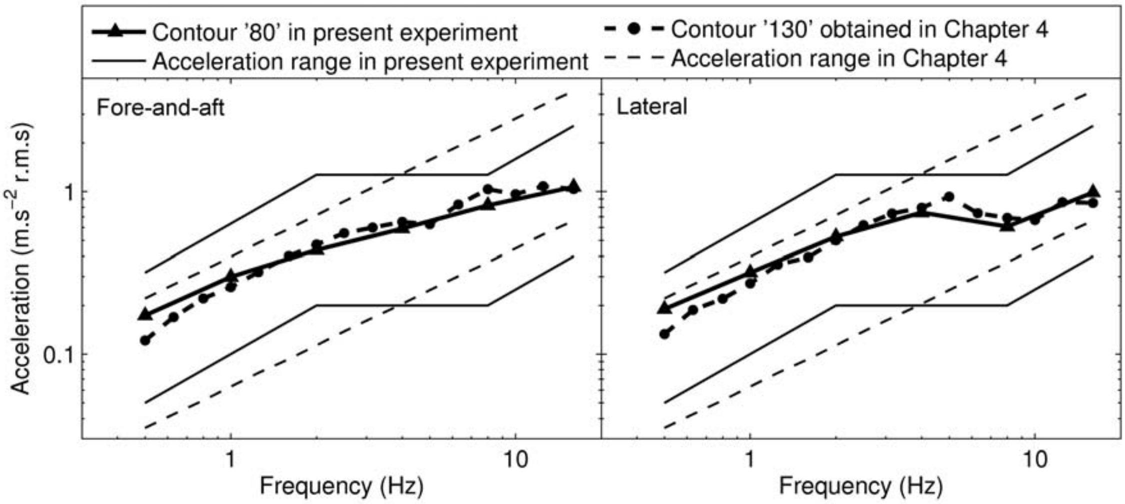


Figure 6.8: Comparison of comfort contours obtained in the present experiment in the 'no support condition' and the contours reported in Chapter 4 (for data, see Appendix E.6, Table E.8.

It appears that the equivalent comfort contours obtained in the two experiments are very similar in shape, despite the differences in the design. In particular, the shape of the contours does not seem to be affected by the range of accelerations used in the experiment. In both directions of horizontal vibration, subjects appeared to be slightly more sensitive to low frequencies (less than about 2 Hz) in Experiment 1 (Chapter 4) than in the present study. This might be due to the difference in the visual field. In the present study, the subjects could see outside the moving cabin, whereas this was not possible in the other study. The restricted view may have increased the difficulty of maintaining balance, thus increasing discomfort at low frequencies.

### 6.4.2 Localization of discomfort

It appears in Figure 6.7 that as frequency increases, discomfort seems to be caused by vibration in lower parts of the body (it shifts from the abdomen to the feet as frequency increases from 0.5 to 16 Hz). This is consistent with the results reported in Section 4.4.3 of Chapter 4. The subjects did not have the possibility to report balance disturbance as the main cause of discomfort in this experiment. Also, arms were not distinguished from shoulders, and the effect of holding a bar appears similar to that of the shoulder support, although the former is thought to have increased vibration of the arms, and the latter, at the shoulders and the torso.

Supports always increased discomfort in areas of the body that they were in contact with:

- Holding a bar increased discomfort in the arms at all frequencies;
- Using a shoulder support also increased vibration in the arms and shoulder; with lateral vibration, it also increased discomfort due to vibration in the torso (0.5 to 2 Hz) and the head (4 to 16 Hz)
- Using a back support when exposed to fore-and-aft vibration caused increased discomfort in the abdomen (0.5 and 1 Hz) and the upper legs and buttock (2 to 16 Hz).

In all cases where the support increased the discomfort (Figure 6.6), the support seems to create discomfort in the buttocks, abdomen, or upper body parts where there was little or no discomfort without support. This suggests that discomfort was increased when new vibration paths were added to the upper body, thus creating discomfort in those sensitive body parts.

### 6.4.3 Effects of supports

The effect of supports on the balance of subjects exposed to fore-and-aft transient motions was investigated by Robert (2006) using supports similar to the vertical bar and the back support employed in the present study. The author concluded that the low-back support increased comfort because it prevented loss of balance being caused by low magnitude motions, whereas the bar did not prevent loss of balance, and a survey showed that a low-back support was the favourite support among passengers in public transport. However, for motion stimuli of high magnitude, when a loss of balance happened, the low-back support did not help recovery of balance, unlike the vertical bar, and so it was judged less efficient in respect of fall prevention. So, the posture that was reported as preferred in the study by Robert (2006) was also the most uncomfortable in the present study at frequencies greater than 2 Hz; however it improved comfort at 0.5 Hz, probably due to the positive effect on postural stability. This, and the improvement of the static discomfort resulting from reducing the pressure on the feet, is probably the reson why it was preferred by passengers.

Holding a horizontal bar 1.05 m above the floor either rigidly or lightly (only so as to prevent loss of balance only) has been shown to affect the transmission of fore-and-aft floor vibration to the heads of standing subjects (Paddan and Griffin, 1993a and 1993b). When holding the bar rigidly, head vibration was increased at frequencies greater than 1.0 Hz but decreased at frequencies less than 1.0 Hz. In the present study, holding a bar increased the discomfort due to head vibration at 4 and 8 Hz (Figure 6.7), and marginally increased global vibration discomfort at frequencies greater than 1.0 Hz, although the increase was only statistically significant at 8 Hz. With 0.5-Hz vibration, discomfort was reduced when holding a bar, although the reduction was not statistically significant (Table 6.5 and Figure 6.5). The trends in the present study are therefore broadly consistent with the biodynamic findings.

When seated, a backrest increases vibration of the head during fore-and-aft excitation but has much less effect on the transmission of lateral vibration (Paddan and Griffin, 1988b). It was suggested that backrests may modify the transmission of vibration to the body in three ways: the addition of a vibration input path close to the head, a change in the dynamic properties of the body due to the modified posture, and a change in forces within the body.

When seated subjects were exposed to vibration in the range 0.2 to 1.6 Hz, a backrest tended to increase the discomfort caused by lateral vibration (Wyllie and Griffin, 2007) but decrease the discomfort caused by fore-and-aft vibration (Wyllie and Griffin, 2009). At higher frequencies (2 to 60 Hz), a backrest appeared to increase the discomfort caused by fore-and-aft vibration and, to a smaller extent, lateral vibration (Parsons *et al.*, 1982).

The main detrimental effects of supports on the discomfort of standing subjects in the present study occurred at frequencies greater than 2 Hz, where the supports are most likely to have increased the transmission of vibration to the upper-body: a back support with fore-and-aft vibration and a shoulder support with lateral vibration. The back support also significantly increased the discomfort caused by lateral vibration in the range 1 to 4 Hz. The effects of the back support in the present study with standing subjects therefore seem broadly consistent with the effects backrests on the discomfort of seated people.

With the shoulder support and the back support, discomfort may have been increased by additional vibration input paths close to the head and upper-body. These inputs will have 'short-circuited' any isolation of vibration offered by the legs over the frequency range 2 to 16 Hz. The isolation of horizontal vibration provided by the legs can be observed in Figure 4.13 in Chapter 4: the transmission of horizontal vibration of the floor to the heads of standing people decreases with increasing frequency of vibration, and is much reduced at frequencies greater than about 2 Hz (Paddan and Griffin, 1993b). This isolation effect can also be observed in Figure 6.7, where discomfort of people standing without support is partly due to vibration of the abdomen at lower frequencies, but is only due to vibration in the legs and feet at 8 and 16 Hz. When using a shoulder support, however, discomfort seemed to be caused by vibration at the head at frequencies greater than 2 Hz, in addition to the arms. Holding a bar also increased the discomfort in the arms but did not increase significantly the global discomfort, so the effect of the shoulder support is probably mainly due to increase of vibration at the head, caused by the addition of a vibration input close to the head. The effect of the back support is less obvious, partly because the body map used in the experiment did not distinguish between the legs, where subjects felt discomfort when they did not use any support, and the buttock, where the back support caused discomfort. However it can still be noted that at frequencies greater than 2 Hz, subjects felt discomfort in the abdomen (and even the torso at 16 Hz), which did not happen when they did not use any support. This is also probably due to the addition of a vibration input point at the bottom of the abdomen, and explains the increase of global discomfort at high frequencies. It does not appear clearly in Figure 6.7 why there was no effect of supports at 0.5 and 1 Hz, but, as shown in Figure 4.13, vibration is naturally transmitted to the upper body at those frequencies, and the supports do not create vibration in areas of the body where it would not otherwise occur; this may be why they do not increase significantly discomfort.

Wyllie and Griffin (2007, 2009) suggested that, with low-frequency non-vertical vibration, a backrest could improve the comfort of seated people. This benefit was observed at frequencies where the body amplified the vibration. With lateral vibration, the backrest restrained the body and prevented this amplification of the motion, but the benefit was observed only at frequencies close to 0.2 Hz (Wyllie and Griffin, 2007). With fore-and-aft vibration, the backrest reduced instability caused by the amplified motion over a wider range of frequencies and reduced discomfort at most frequencies in the range 0.2 to 1.6 Hz (Wyllie and Griffin, 2009). The natural sway of standing people is greatest at frequencies less than 1 Hz (Soames and Atha, 1982), consistent with the peak in floor-to-head transmissibility between 0.4 and 0.8 Hz, as shown in Figure 4.13 (Paddan and Griffin, 1993b). In the present experiment, the supports that increased discomfort at frequencies greater than 2 Hz (i.e. the back support with fore-and-aft vibration and the shoulder support with lateral vibration) also reduced discomfort at 0.5 Hz (Figure 6.5, Table 6.5), consistent with the supports reducing upper-body motion at the low frequency resonances and thereby reducing discomfort at low frequencies.

### 6.4.4 Comparison with standards

Frequency weightings were derived from the equivalent comfort contours by inverting them and normalizing them to the same value (i.e. a weighting of 1.0) at 0.5 Hz. In Figure 6.9, these weightings are compared with the weightings advocated in current International and

Table 6.6: Frequency weighting curves advocated in BS 6841 (1987) and ISO 2631-1 (1997) or derived from these standards.

| **Point and direction** | **Weighting curve** | **Multiplying factor** |
|---|---|---|
| $x$-axis (standing or seated) | $W_d$ | $k = 1$ |
| $y$-axis (standing or seated) | $W_d$ | $k = 1$ |
| $x$-axis, backrest | $W_c$ | $k = 0.8$ |
| $y$-axis, backrest | $W_d$ | $k = 0.5$ |
| $x$-axis, seat + backrest | $W_x(f) = \left\{W_d(f)^2 + [0.8W_c(f)]^2\right\}^{1/2}$ | $k = 1$ |
| y-axis, seat + backrest | $W_y(f) = \left\{W_d(f)^2 + [0.5W_d(f)]^2\right\}^{1/2}$<br>(i.e. $1.12W_d(f)$) | $k = 1$ |

British standards, namely ISO 2631-1 (1997) and BS 6841 (1987). In the standards, the weighting $W_d$ is advocated for fore-and-aft and lateral vibration at the seat for seated persons and also at the floor for standing persons. For a seated person, if there is also vibration from a backrest, the overall discomfort is evaluated from the root-sum-of-squares of the weighted components at the seat and the backrest. At the backrest, fore-and-aft vibration should be weighted using $W_c$ with a multiplying factor of 0.8, and lateral vibration using $W_d$ with a multiplying factor of 0.5 (as summarized in Table 6.6). If the seat pan and the backrest are rigid so that they have the same vibration, the overall vibration discomfort due to a single frequency of vibration is given by the acceleration multiplied by:

$$W_x(f) = \left\{W_d(f)^2 + [0.8W_c(f)]^2\right\}^{1/2} \tag{6.4}$$

for fore-and-aft vibration, and by:

$$W_y(f) = \left\{W_d(f)^2 + [0.5W_d(f)]^2\right\}^{1/2} = 1.12W_d(f) \tag{6.5}$$

for lateral vibration (Table 6.6).

The weightings obtained in the 'free' posture (i.e. with no support) differ from the weighting $W_d$ advocated in the standards, as found in Chapter 4: the $W_d$ weighting is approximately unity at frequencies between 0.5 and 2 Hz, whereas the experimentally determined weighting decreases with increasing frequency over this range. When subjects used the back support, their posture might be likened to that of a seated person with a vibrating backrest, but the weightings that should be applied for a seated person (i.e. $W_x$, defined in Equation 6.4, for fore-and-aft vibration and $W_d$ for lateral vibration) do not match the experimentally determined weightings obtained for people standing with the back support (Figure 6.9).

The weighting obtained with lateral vibration and the shoulder support is close to the $W_x$ weighting applicable to seated persons exposed to fore-and-aft vibration with a backrest

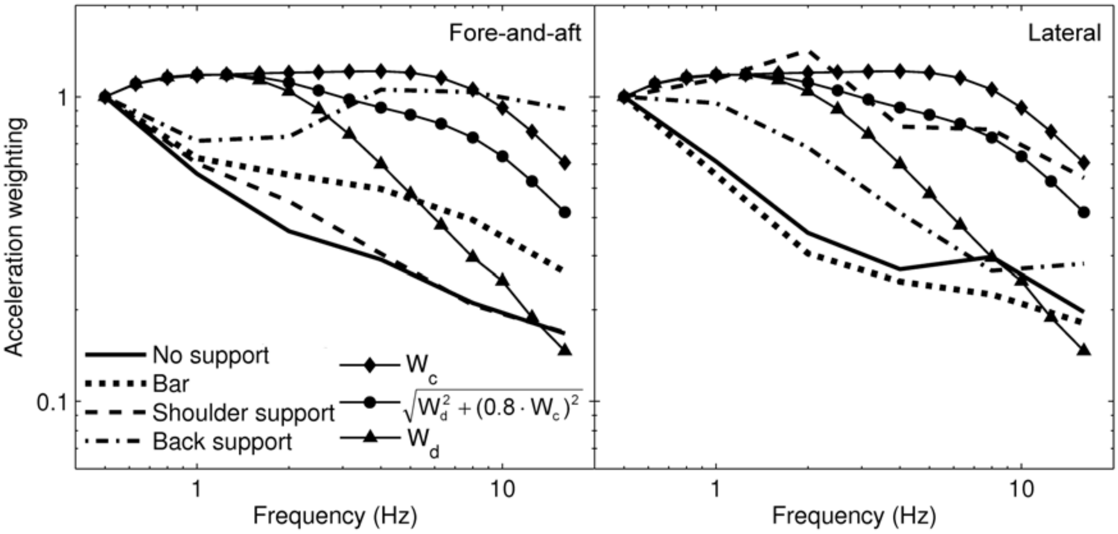


Figure 6.9: Comparison of experimental median weightings and standard weightings.

(Figure 6.9). For both a seated person exposed to fore-and-aft vibration with a backrest and a standing person exposed to lateral vibration with a shoulder support, vibration is transmitted directly to the chest - explaining the similarity in the response in these two situations.

## 6.5 Conclusion

The discomfort of standing persons caused by fore-and-aft or lateral vibration is not greatly affected by holding a vertical bar with an 'unlocked' elbow. However, at frequencies of vibration greater than about 2 Hz, the discomfort caused by fore-and-aft vibration is increased by leaning back against a back support, and the discomfort caused by lateral vibration is increased by leaning sideways on a shoulder support. A back support also increases discomfort caused by lateral vibration over the range 1 to 4 Hz. A back support reduces the discomfort caused by 0.5-Hz fore-and-aft vibration, and a shoulder support reduces the discomfort caused by 0.5-Hz lateral vibration. Weightings showing the effects of supports are offered so as to weight motions and take account of alternative postural supports when assessing the vibration discomfort of standing passengers.

The frequency-dependence of discomfort when standing without support or when holding only a vertical bar is not consistent with the frequency weightings provided for predicting the discomfort of standing people in current standards (ISO 2631-1, 1997, and BS 6841, 1987). The discomfort caused by lateral vibration when standing with a shoulder support is broadly consistent with the standard method of predicting the discomfort of people seated with a backrest when exposed to fore-and-aft vibration.

# Chapter 7

# Evaluation of random and transient motions

## 7.1 Introduction

In Chapters 4, 5 and 6, the effect of frequency, direction and postural supports on vibration discomfort were investigated. However, the vibration stimuli used in those experiments were sinusoidal vibrations, which are not encountered in real situations where people are exposed to vibration. Vibration usually has a broader frequency range and includes transient peaks, so it is better represented by random vibration. For this reason it is necessary to determine how the results from previous chapters can be applied to random vibration including transients; this means a method is needed to evaluate such stimuli.

Methods for evaluating the vibration of seated and standing people are advocated in British Standard 6841 (1987) and International Standard 2631-1 (1997). The basic method requires the calculation of the root-mean-square (r.m.s.) value of the frequency-weighted acceleration time history, $a(t)$, over a finite period of time, $T$ (ISO 2631-1, 1997, Section 6.1, Equation 7):

$$r.m.s. = \left[\frac{1}{T}\int_0^T a(t)^2 dt\right]^{1/2} \tag{7.1}$$

Frequency weightings have been determined from equivalent comfort contours showing the vibration magnitudes required to produce similar discomfort at different frequencies. Such studies have mostly used constant magnitude sinusoidal vibration and, when the r.m.s. method is applied to evaluate vehicle ride, variations in vibration magnitude over the measurement period tend to be ignored.

Equivalent comfort contours for seated people exposed to sinusoidal vibration have been compared with equivalent comfort contours obtained with one-third octave and octave bands of random vibration over the range 3.15 to 20 Hz (Griffin, 1976) and over the range 2 to 10 Hz (Donati *et al.*, 1983). Both studies showed greater sensitivity to random vibration than sinusoidal vibration of the same r.m.s. magnitude, with the difference varying between about 0.5 dB and 2 dB, depending on the frequency of vibration. The difference between sensitivity to random and sinusoidal vibration when using the r.m.s. method shows the need for an alternative measure more suitable for evaluating all types of motion, including sinusoidal, random, and transient vibration.

The r.m.s. method was also found to be unsatisfactory for the evaluation of motions containing transients; for example, Howarth and Griffin (1991) found that the discomfort of motions containing peaks of acceleration was approximately constant when the number of peaks varied but the r.m.q value was held constant. Alternative methods are advocated in standards for evaluation of transient motions. One of these methods is the root-mean-quad (r.m.q.) method, similar to the root-mean-square, but with an exponent of 4 (ISO 2631-1, 1997, Section 6.3.2, Equation 5):

$$r.m.q. = \left[\frac{1}{T}\int_0^T a(t)^4 dt\right]^{1/4} \tag{7.2}$$

Another method is the maximum transient vibration value ($MTVV$), which is the maximum value over the measurement period of the running r.m.s. value (i.e. the r.m.s. magnitude of the vibration over a running window of duration $\tau$; ISO 2631-1, 1997, Section 6.3.1, Equations 2 and 4):

$$MTVV = \max\left\{\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w(t)^2 dt\right]^{1/2}\right\}_{t_0=\tau..T} \tag{7.3}$$

There is little evidence from which to identify an optimum value for the integration time, $\tau$, that can greatly affect the measured value, although ISO 2631 (1997) recommends a 1-s integration time.

The objective of the study reported in this paper was to find a method suitable for evaluating both statistically stationary and transient vibration so as to predict the discomfort of standing persons exposed to the fore-and-aft, lateral, and vertical vibration of a floor. Both approaches suggested in the standards (i.e. changing the exponent used in the r.m.s. value from 2 to 4, or the running r.m.s. with a short integration window) were considered. It was hypothesized that motions having a range of crest factors could be evaluated by the function $f_{\lambda,\tau}$:

$$f_{\lambda,\tau}(a) = \max\left\{\left[\frac{1}{\tau}\int_{t_0}^{t_0+\tau} |a_w(t)|^{\lambda} dt\right]^{1/\lambda}\right\}_{t_0=0..T-\tau} \tag{7.4}$$

where the exponent, $\lambda$, and the window size, $\tau$, were to be determined from the study.

## 7.2 Method

### 7.2.1 Stimuli

Subjects were exposed to sinusoidal and octave-bandwidth random vibration of a flat surface on which they stood. The vibration stimuli were 6 seconds in duration, including a 1.5-second cosine-tapered start and a 1.5-second cosine-tapered end. The nominal frequencies of the motions were 1 Hz and 8 Hz. The experiment consisted of three studies. In each study, the vibration was in one of the three directions: fore-and-aft, lateral, or vertical.

Motion stimuli were presented in pairs, with the first stimulus (the reference motion) a sinusoidal vibration and the second stimulus (the test motion) an octave-bandwidth random vibration. The reference motion and the test motion always had the same nominal frequency. The magnitudes and frequencies of the reference and test motions are shown in Table 7.1.

Each subject was exposed to a total of 126 test motions in each session: all possible combinations of two frequencies (1 Hz and 8 Hz), nine vibration magnitudes (Table 7.1), and seven different waveforms of random vibration. The seven random waveforms were selected to have specific values for the ratio of their root-mean-quad value to their root-mean-square value: 1.19, 1.28, 1.36, 1.44, 1.52, 1.60, and 1.68. Examples of the waveforms are shown in Figure 7.1.

Table 7.1: Magnitudes of the test stimuli (all magnitudes are in m.s$^{-2}$ r.m.s.).

| | Horizontal | | Vertical | |
|---|---|---|---|---|
| | 1 Hz | 8 Hz | 1 Hz | 8 Hz |
| Reference magnitude | 0.20 | 0.80 | 0.50 | 0.20 |
| Test magnitude 1 | 0.13 | 0.5 | 0.32 | 0.13 |
| Test magnitude 2 | 0.14 | 0.57 | 0.35 | 0.14 |
| Test magnitude 3 | 0.16 | 0.64 | 0.40 | 0.16 |
| Test magnitude 4 | 0.18 | 0.71 | 0.45 | 0.18 |
| Test magnitude 5 | 0.20 | 0.80 | 0.50 | 0.20 |
| Test magnitude 6 | 0.22 | 0.90 | 0.56 | 0.22 |
| Test magnitude 7 | 0.25 | 1.01 | 0.63 | 0.25 |
| Test magnitude 8 | 0.28 | 1.13 | 0.71 | 0.28 |
| Test magnitude 9 | 0.32 | 1.27 | 0.79 | 0.31 |

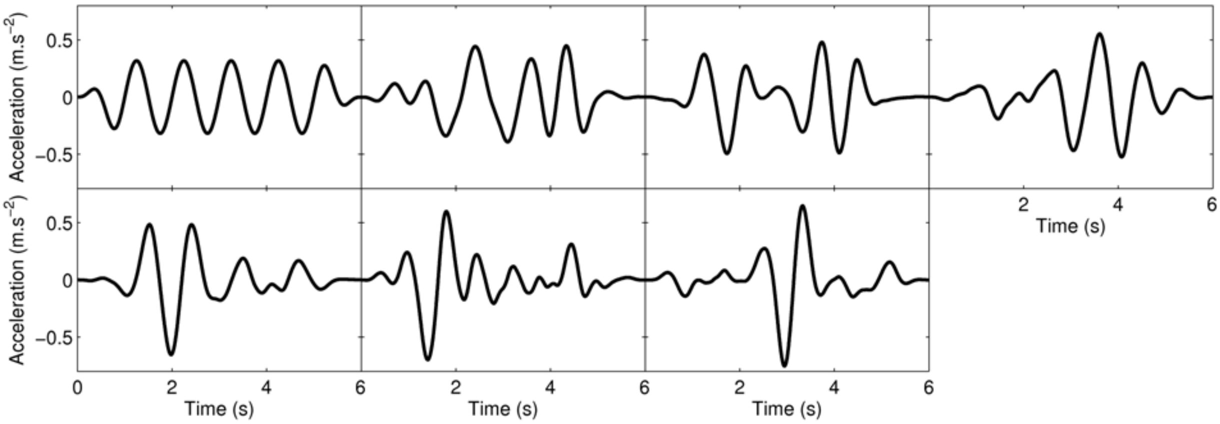


Figure 7.1: Example of the seven random waveforms used in the experiment. All motions shown have the same r.m.s. magnitude. The r.m.q./r.m.s. ratio are respectively: 1.19, 1.28, 1.36, 1.44, 1.52, 1.60, and 1.68.

### 7.2.2 Posture and visual field

The subjects stood without shoes, but with socks, on a wooden platform. They kept an upright posture with knees locked. Their feet were parallel and separated so that their lateral base of support (distance between the outer edges of their feet) was 350 mm, the median shoulder width for adult males (Pheasant, 1988).

The subjects wore a pair of headphones delivering broadband noise at 65 dB(A) and were asked to close their eyes during exposure to vibration stimuli.

The subjects wore a loose harness in case they should fall. The harness did not support the subjects or restrict their movement when standing as instructed. The harness was secured to an aluminium frame mounted on the vibrator platform. The frame had dimensions 975 mm x 1270 mm x 2000 mm (length x width x height) when mounted for fore-and-aft and lateral vibration, and 670 mm x 1270 mm x 2000 mm when mounted for vertical vibration (Figure 7.2).

### 7.2.3 Subjects

Twenty male students and staff of the University of Southampton participated in each experiment. Fifteen subjects participated in each of the three studies. The physical characteristics of the subjects who participated in the study fore-and-aft, lateral, and vertical vibration are reported in Tables 7.2, 7.3, and 7.4 respectively.

Each study lasted about 90 minutes. The studies were approved by the Human Experimentation Safety and Ethics Committee of the ISVR at the University of Southampton.

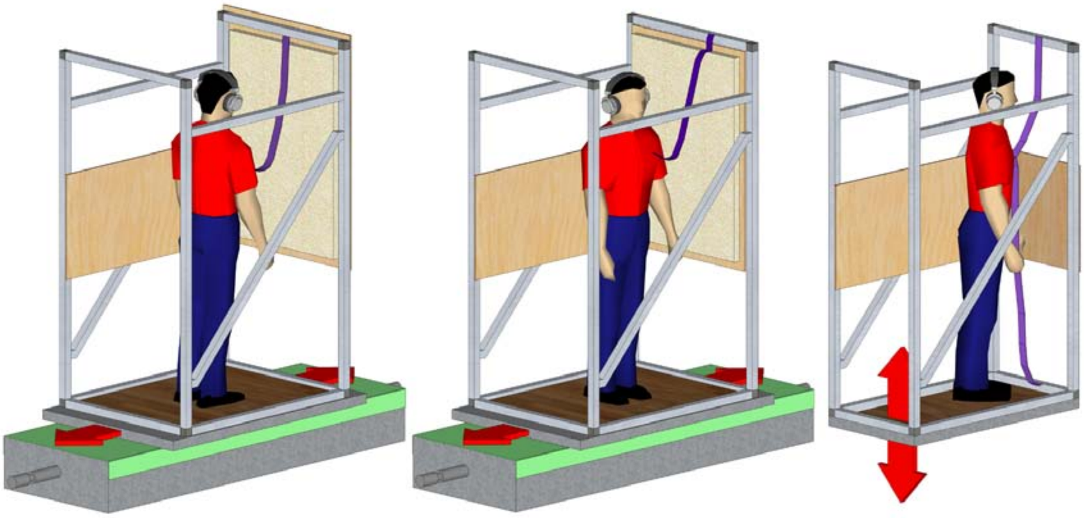


Figure 7.2: Experimental setup used for fore-and-aft, lateral, and vertical vibration.

### 7.2.4 Equipment

The vibration was produced by a 1-metre stroke hydraulic horizontal vibrator, controlled by a Pulsar Digital Controller (Servotest Systems, Egham, UK) and a 1-metre stroke hydraulic vertical vibrator, controlled by a similar system. The motion stimuli were generated in Matlab (version R2009a) using the Matlab Toolbox HVLab HRV (version 1.1) developed by the Human Factors Research Unit (University of Southampton).

The vibration of the platform was monitored using an Entran EGCSY-240D*-10 piezoresistive accelerometer secured to the table of the vibrator, with the signal amplified using a FYLDE FE-366-TA dual channel amplifier and sampled by the Pulsar Digital Controller software at 256 samples per second after low pass filtering at 40 Hz.

### 7.2.5 Procedure

The method of magnitude estimation was employed to determine the discomfort caused by each of the test motions relative to the discomfort caused by the reference motion.

Motion stimuli were presented in pairs. The second vibration stimulus (test) was one of the 126 test stimuli (see Section 7.2.1). The first vibration stimulus (reference) was a sinuoidal motion, in the same direction and at the same frequency as the test (1 Hz or 8 Hz). The magnitudes of the reference motions for all directions and frequencies are indicated in Table 7.1. The magnitudes of the reference stimuli at 1 Hz and 8 Hz were chosen based on the results of Chapter 4 so that they would produce approximately similar degrees of discomfort.

Fore each axis of vibration, the order of presentation of the 126 test stimuli was completely randomized independently for each subject.

Table 7.2: Physical characteristics of the subjects of the study with fore-and-aft vibration. Subjects 1 to 15 participated in all three studies.

| Subject | Height (cm) | Weight (kg) | Age (years) |
|---|---|---|---|
| 1 | 174 | 70 | 30 |
| 2 | 178 | 60 | 26 |
| 3 | 175 | 90 | 29 |
| 4 | 165 | 50 | 26 |
| 5 | 167 | 85 | 29 |
| 6 | 178 | 74 | 23 |
| 7 | 167 | 61 | 26 |
| 8 | 178 | 80 | 25 |
| 9 | 168 | 82 | 30 |
| 10 | 173 | 65 | 22 |
| 11 | 169 | 61 | 24 |
| 12 | 167 | 70 | 22 |
| 13 | 170 | 55 | 28 |
| 14 | 183 | 75 | 28 |
| 15 | 190 | 88 | 30 |
| x16 | 176 | 76 | 28 |
| x17 | 176 | 72 | 25 |
| x18 | 182 | 73 | 20 |
| x19 | 190 | 80 | 28 |
| x20 | 171 | 85 | 28 |
| Median | 175 | 74 | 27 |

Table 7.3: Physical characteristics of the subjects of the study with lateral vibration. Subjects 1 to 15 in Table 7.2 also participated in this study.

| Subject | Height (cm) | Weight (kg) | Age (years) |
|---|---|---|---|
| y16 | 176 | 76 | 28 |
| y17 | 180 | 65 | 30 |
| y18 | 182 | 73 | 20 |
| y19 | 174 | 59 | 24 |
| y20 | 177 | 69 | 30 |
| Median | 176 | 73 | 28 |

The method of magnitude estimation (Section 3.4.1) was used. After the presentation of a pair of reference and test motions, subjects were asked to provide a number reflecting the discomfort caused by the test motion assuming the discomfort caused by the reference motion was 100 (Appendix A.4). The subjects could ask for the presentation of a pair of motions to be repeated if they were not sure how to respond.

After completing the magnitude estimation of all motions, subjects were presented with selected motions in a random order and asked to state whether the main cause of discomfort

Table 7.4: Physical characteristics of the subjects of the study with vertical vibration. Subjects 1 to 15 in Table 7.2 also participated in this study.

| Subject | Height (cm) | Weight (kg) | Age (years) |
|---|---|---|---|
| z16 | 170 | 60 | 26 |
| z17 | 175 | 70 | 35 |
| z18 | 170 | 83 | 38 |
| z19 | 190 | 80 | 28 |
| z20 | 171 | 85 | 28 |
| Median | 176 | 73 | 28 |

was postural instability, dizziness or vibration in a specific part of the body. If most discomfort arose from sensations in the body, they reported the location of the sensation using a body map (Appendices A.4.1 and A.4.2). For each of the seven waveforms, two motion magnitudes were presented (at the 5th magnitude in Table 7.1, and at a magnitude corresponding approximately to a subjective rating of 100, based on the previous judgements of the subject).

### 7.2.6 Data processing

It was hypothesized that the discomfort caused by the random motions could be predicted from the acceleration time history with the function $f_{\lambda,\tau}$ (Equation 7.4). If $\lambda = 2$, the evaluation function corresponds to the maximum transient vibration value ($MTVV$) with a window size, $\tau$, as defined in ISO 2631-1 (1997). If $\lambda = 2$ and $\tau = 6\ s$ (the total duration of the motions stimuli), the evaluation function corresponds to the root-mean-square (r.m.s.) value. If $\lambda = 4$ and $\tau = 6s$, the function corresponds to the root-mean-quad (r.m.q.) value.

The objective was to identify, for each subject, a set of seven vibration stimuli (having different r.m.q./r.m.s. ratios) that were subjectively equivalent to each other and to discover an evaluation function that yielded identical values for all seven motions.

The evaluation function $f_{\lambda,\tau}$ was considered biased if it either over-evaluated or under-evaluated peaky motions compared to stationary motions (i.e. if a positive or negative correlation was observed between the r.m.q./r.m.s. ratios and the values yielded by the $f_{\lambda,\tau}$ function). The evaluation function $f_{\lambda,\tau}$ was considered optimum if the values it yielded for the waveforms considered to be equivalent by a subject were not correlated with the values of the r.m.q./r.m.s. ratios.

The method is summarized in Figures 7.3 and 7.4.

#### 7.2.6.1 Linear regressions

Stevens power law was used to relate the magnitude of the sensation induced by a motion, $\psi$, to the physical magnitude of the motion, $\varphi$, (Stevens, 1975):

$$\psi = k\varphi^n \tag{7.5}$$

where $k$ (the constant in Stevens power law) and $n$ (the exponent) are assumed to be constant for a given stimulus. In the present case,$\varphi$ is the magnitude of the vibration, which can be evaluated by different methods, and $\psi$ is the subjective magnitude felt and reported by the subjects.

Equation (7.5) can be written in logarithmic form:

$$\log(\psi) = \log(k) + n \cdot \log(\varphi) \tag{7.6}$$

By performing linear regression between the experimental values of $\log(\psi)$ and $\log(\varphi)$, estimates of the constant $k$ and the exponent $n$ were obtained for each subject and for each waveform.

For the linear regression, the method of weighted least squares, using bisquare weights, was used (Section 3.4.3). This method has the advantage of not being biased by outlier values caused by inconsistent answers.

#### 7.2.6.2 Equivalent magnitudes

After individual values of the constant, $k$, and the exponent, $n$, had been obtained for each subject and each waveform, it was possible to determine the magnitude of the waveform corresponding to a magnitude estimate of 100 (i.e. equivalent to the sinusoidal reference motion):

$$\varphi_{eq} = \left(\frac{100}{k}\right)^{1/n} \tag{7.7}$$

The equivalent waveform could then be constructed, by scaling the waveform to this equivalent r.m.s. magnitude. By scaling each of the seven waveforms in this way, seven equivalent motions were obtained for each subject (Figure 7.3). The r.m.q./r.m.s. ratio (Figure 7.1) was not affected by this procedure.

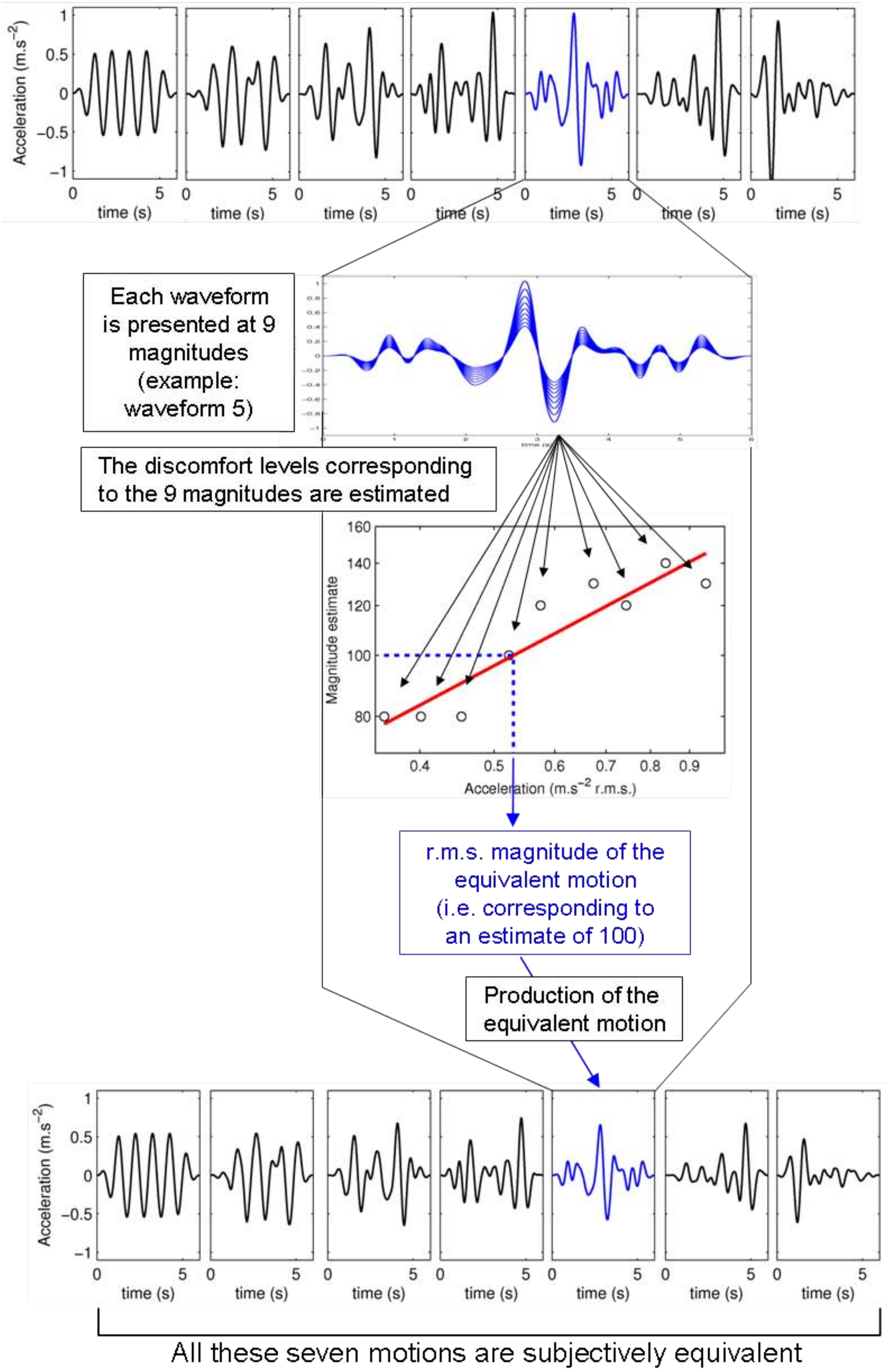


Figure 7.3: Method used for post-processing. Part 1: production of equivalent motions.

#### 7.2.6.3 Optimal $\lambda$ values

The equivalent magnitudes obtained for each of the seven waveforms from each subject were then pooled to obtain a globally unbiased evaluation of vibration. For values of $\lambda$ between 0.1 and 20, and values of $\tau$ between 0.1 s and 6 s, the $f_{\lambda,\tau}$ values (see Equation 7.4) of the 140 subjectively equivalent motions (i.e. the judgements of 7 stimuli by 20 subjects) were calculated, and the Spearman rank-order correlation coefficients between the r.m.q./r.m.s. ratios and the $f_{\lambda,\tau}$ values were calculated.

For any given $\tau$, the correlation was negative for low values of $\lambda$ (i.e. the discomfort produced by peaky stimuli, having high r.m.q./r.m.s. ratios, was underestimated relative to the discomfort produced by vibrations having low ratios). In contrast, high values of $\lambda$ overestimated peaky motions, and yielded a positive correlation. For any given $\tau$, the optimal value of the exponent, $\lambda$, was assumed to be the value that corresponded to a zero correlation coefficient (Figure 7.4), since this indicates there was no bias towards overestimating or underestimating peaky motions (with higher r.m.q./r.m.s. ratios) compared to stationary motions (with lower r.m.q./r.m.s. ratios).

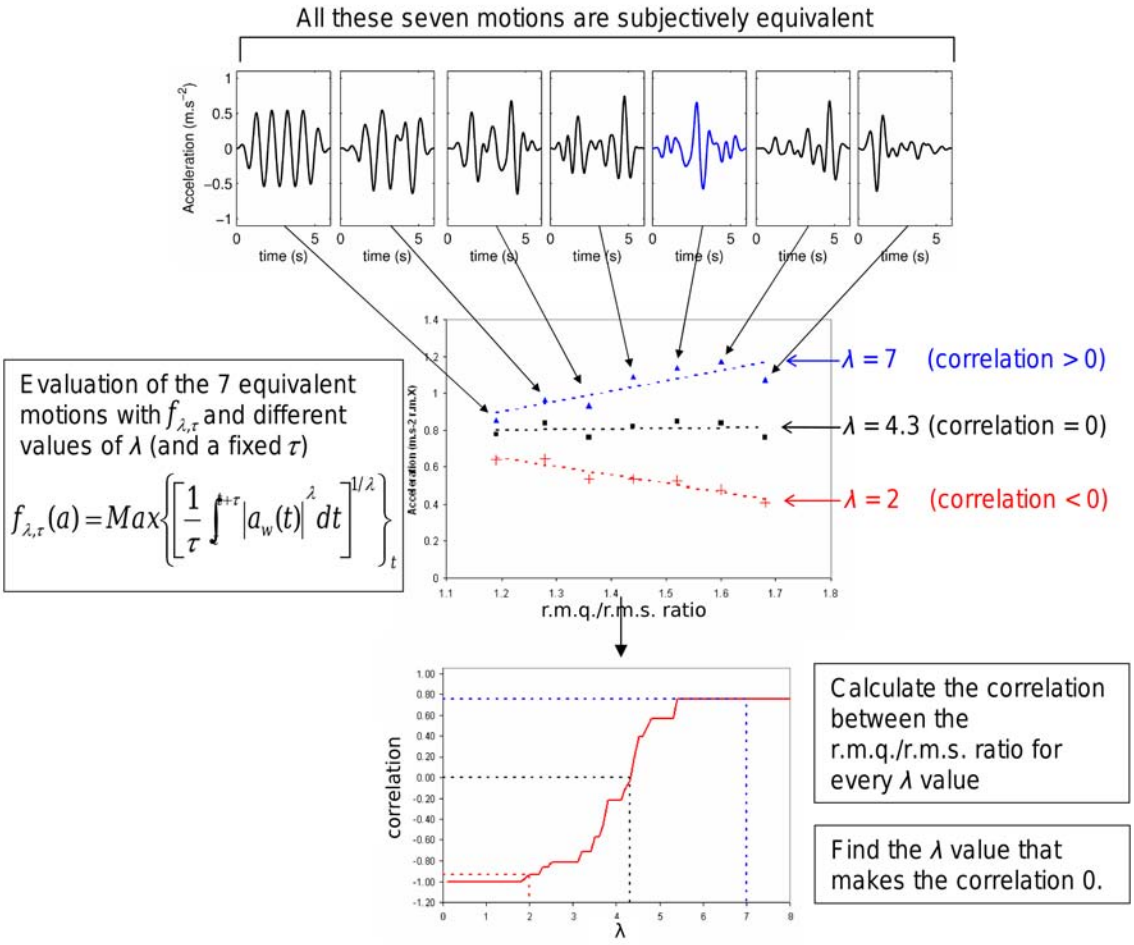


Figure 7.4: Method used for post-processing. Part 2: estimation of the optimal $\lambda$-value.

For values of $\tau$ between 0.25 s and 6 s, the optimal $\lambda$ value was calculated. All the $(\tau, \lambda)$ pairs obtained with this method correspond to a zero correlation. This suggests that all corresponding $f_{\lambda,\tau}$ functions are suitable functions.

## 7.3 Results

### 7.3.1 Localization of discomfort

At both frequencies and in each direction of vibration, subjects were presented with vibrations with each of the seven waveforms and asked to report the cause of discomfort. They could indicate that the main cause of discomfort was vibration in a part of the body (that they were asked to specify using the body map shown in Figure 4.3), loss of balance, or dizziness. The magnitude of each vibration was the equivalent magnitude for this subject (see Section 7.2.6.2), which means that all vibration stimuli used in this part of the experiment caused an equivalent discomfort for the subjects. The results are shown in Figure 7.5, where the proportion of subjects reporting, respectively, discomfort in the lower body (feet and legs), discomfort in the upper body, loss of balance or dizziness is shown as a function of the r.m.q./r.m.s. ratio.

The results are consistent with those of Chapter 4 (Figure 4.11): at 8 Hz, horizontal vibration causes discomfort mainly in the legs and feet, as the legs isolate the upper body from the vibration. This effect does not occur with vertical vibration, which causes discomfort in both the upper body and the lower body. At 1 Hz, horizontal vibration causes discomfort mainly because of loss of balance, particularly fore-and-aft vibration. Vertical vibration creates dizziness and losses of balance.

The results show that the mechanisms of discomfort are very different at 1 Hz and at 8 Hz. It was hypothesized that the cause of discomfort would depend on the waveform, particularly with 1-Hz vibration as more peaky vibration may cause a greater disturbance to balance. However, this was not the case. For horizontal vibration and at both frequencies, the occurrence of loss of balance was independent of the r.m.q./r.m.s. ratio ($p = 0.46$ for 1-Hz fore-and-aft vibration, $p = 0.55$ for 1-Hz lateral vibration, Cochran). With 1-Hz vertical vibration, the occurrence of dizziness was dependent on the waveform ($p = 0.048$, Cochran), as it was progressively replaced by loss of balance as the peakiness increased; but if loss of balance and dizziness were grouped together, the occurrence of these other causes was independent on the peakiness ($p = 0.83$, Cochran).

It can be concluded that the cause of discomfort does not depend on the waveform; this suggests that the same evaluation method can be used for more or less peaky vibrations. On the other hand, since the mechanisms of discomfort are very different at 1 Hz and 8 Hz, the optimal evaluation method might be different at both frequencies.

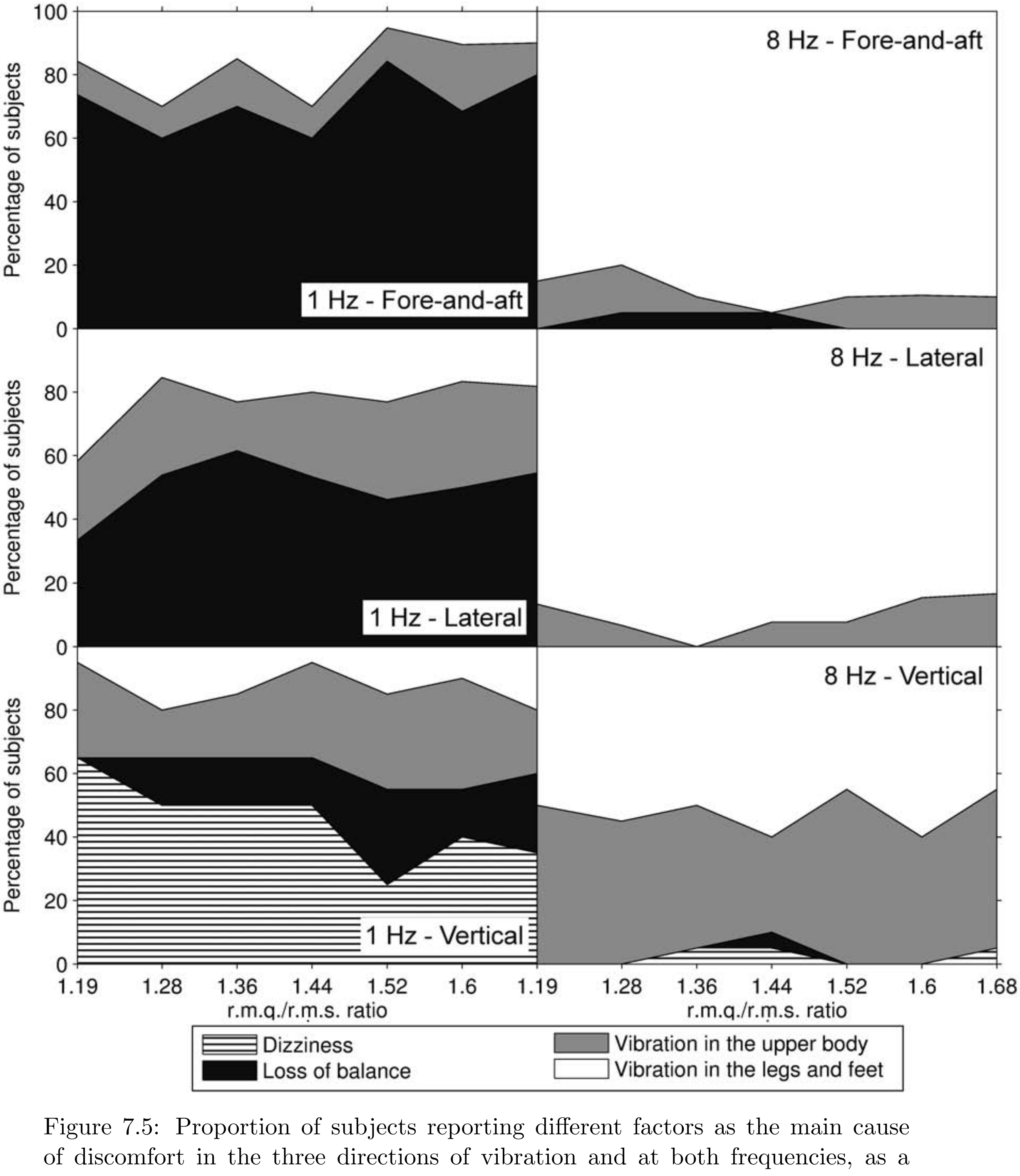


Figure 7.5: Proportion of subjects reporting different factors as the main cause of discomfort in the three directions of vibration and at both frequencies, as a function of the r.m.q./r.m.s. factor.

### 7.3.2 Optimal $(\lambda, \tau)$ pairs

The optimal values for the exponent $\lambda$, obtained as explained in Section 7.2.6.3 for values of $\tau$ between 0.25 s and 6 s, are shown in Figure 7.6 for each of the three directions of vibration and both frequencies of vibration. For the shortest values of $\tau$, it was not possible to find $\lambda$ values corresponding to zero correlation, so no value is reported.

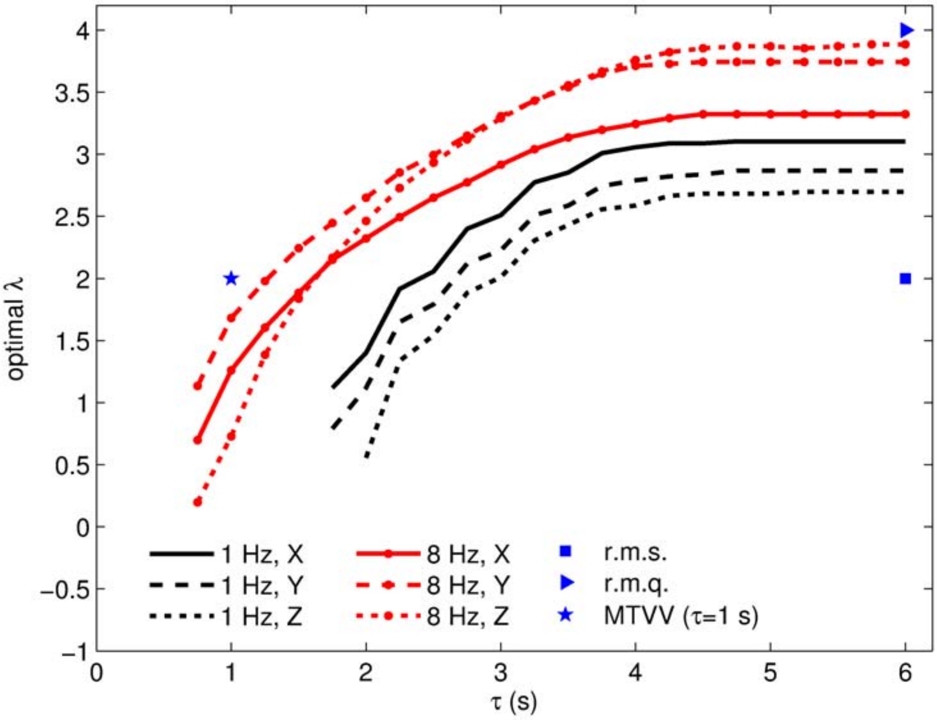


Figure 7.6: Optimal $\lambda$ value for different $\tau$ values, obtained with all waveforms and all subjects pooled together. Each point corresponds to a $(\lambda, \tau)$ pair for which the function $f_{\lambda,\tau}$ (Equation 7.4) is unbiased (i.e. it does not underestimate or overestimate the discomfort of peaky motions). The $(\lambda, \tau)$ pairs corresponding to the methods advocated by standards are shown for comparison.

When $\tau = 6$ (the duration of the test motions), the function $f_{\lambda,\tau}$ is equivalent to the root-mean-square (r.m.s.) if the exponent $\lambda$ is 2 and equivalent to root-mean-quad (r.m.q.) if $\lambda$ is 4. The optimal $\lambda$ values for $\tau$=6 s are reported in Table 7.5. The results suggest that if the overall value of the vibration is determined in a manner similar to the true r.m.s. value, the exponent should be in the range 2.7 to 3.9, depending on the frequency and direction of vibration.

Table 7.5: Optimal $\lambda$ values for $\tau = 6$ s.

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| 1 Hz | 3.1 | 2.9 | 2.7 |
| 8 Hz | 3.3 | 3.7 | 3.9 |

In International Standard 2631-1:1997, it is suggested that the maximum transient vibration value (MTVV) may be used for evaluating motions containing transients and recommends that the time constant, $\tau$, should be 1 s. The MTVV corresponds to $f_{\lambda,\tau}$ with $\lambda = 2$. If the MTVV method was so be used, the window size $\tau$ must be such that the evaluation function $f_{2,\tau}$ is unbiased. To determine the most appropriate window size, the $\tau$ values corresponding to a zero correlation with $\lambda = 2$ were determined from the data shown in Figure 7.6. As shown in Table 7.6, the optimum averaging time, $\tau$, varied from 1.3 to 3.0 s, depending on the frequency and direction of vibration.

Table 7.6: Optimal $\tau$ values for $\lambda = 2$.

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| 1 Hz | 2.4 s | 2.7 s | 3.0 s |
| 8 Hz | 1.6 s | 1.3 s | 1.6 s |

### 7.3.3 Comparison of the optimal $(\lambda, \tau)$ pairs

For both frequencies (1 Hz and 8 Hz) and all three directions of vibration (fore-and-aft, lateral and vertical), $(\lambda, \tau)$ pairs corresponding to zero correlation were obtained for $\tau$ values between 2 s and 6 s for 1-Hz vibration, and between 1 s and 6 s for 8-Hz vibration (Figure 7.6). All those pairs provide an unbiased $f_{\lambda,\tau}$ function, but the function might provide a better prediction with some of them.

The $f_{\lambda,\tau}$ functions associated with the optimal $(\lambda, \tau)$ pairs were compared. For each subject, the seven equivalent motions are subjectively equivalent, so an evaluation function needs to be unbiased, but also provide similar estimates for the seven motions. Therefore, a better $f_{\lambda,\tau}$ function yields less dispersed evaluations for the seven equivalent motions. The dispersion between the seven values was measured by their coefficient of variation (the ratio of the standard deviation to the mean). These coefficients of variation, calculated with the $f_{\lambda,\tau}$ functions associated with optimal $(\lambda, \tau)$ pairs (i.e., pairs shown in Figure 7.6) were used in order to determine whether some of those pairs provided a better evaluation.

The median coefficients of variation are shown in Figure 7.7 as a function of $\tau$ (for each value of $\tau$, the optimal value of $\lambda$ shown in Figure 7.6 was used). A smaller coefficient of variation at a given value of $\tau$ means that the function $f_{\lambda,\tau}$ obtained with the given value of $\tau$ and the corresponding optimal value of $\lambda$, is better.

The effect of $\tau$ on the coefficients of variation is minor. No significant effect was found for vertical vibration at 1 Hz ($p = 0.12$, Friedman) or 8 Hz ($p = 0.74$, Friedman). For horizontal vibration the coefficient of variation depended on $\tau$ ($p < 0.03$, Friedman). Paired comparisons using the Wilcoxon test showed that the coefficient of variation tended to decrease as $\tau$ increased, suggesting that higher values of $\tau$, and in particular 6 s, are better, although the difference was minor, as shown in Figure 7.7.

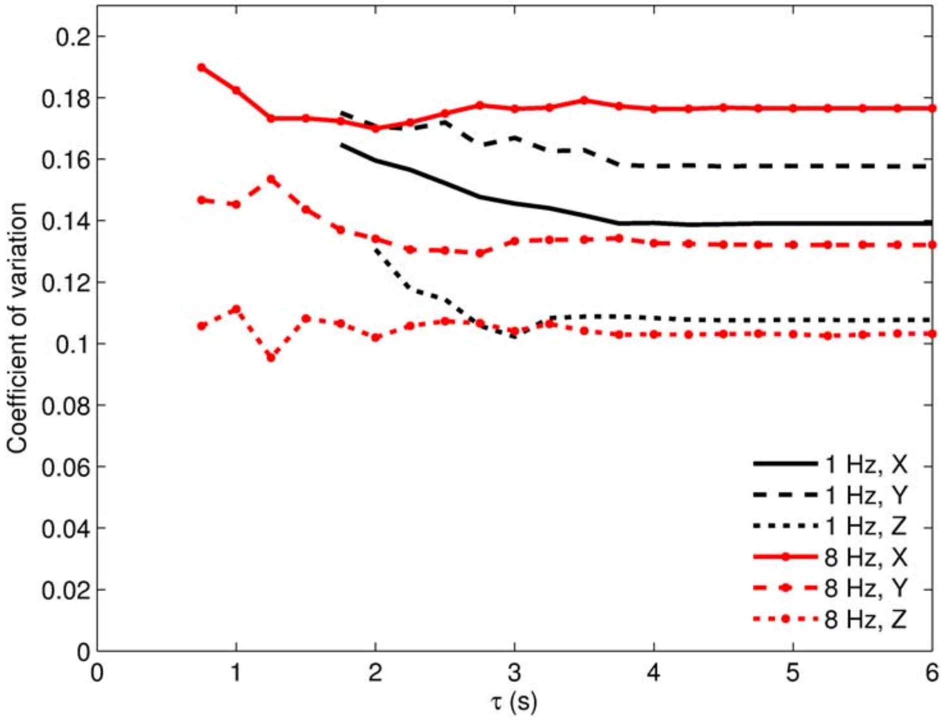


Figure 7.7: Median coefficient of variation of the $f_{\lambda,\tau}$ values of the seven equivalent waveforms for each subject, with $\lambda$ being the optimal value shown in Figure 7.6 at each $\tau$ value.

## 7.4 Discussion

### 7.4.1 Choice of the method

#### 7.4.1.1 The method of constant stimuli

In a preliminary phase of the experiment, a variation of the method of constant stimuli (Section 2.2.3.4 of the literature review) was used instead of the method of magnitude estimation. With this method, the pairs of stimuli presented were the same as described in Section 7.2.1.

The method only differed with the method of magnitude estimation, eventually retained, in the question asked to the subjects: instead of estimating the magnitude of the second stimulus compared to the first one, the subjects were asked to state which of the two vibrations (the reference and the test) was the ‘worst’. The wording was chosen in order to include all negative effects of vibration (the word ‘discomfort’ may be understood by some subjects as excluding postural stability). The objective of the experiment, as explained in Section 7.2.6.2, was to determine the magnitude of the test vibration equivalent to the sinusoidal reference vibration (i.e., causing an equivalent discomfort). It was hypothesized that:

- when the test stimulus was presented at the lowest of the nine magnitudes (Table 7.1), it would cause less discomfort than the sinusoidal reference, so the answer to the question "which of the two motions is worst" would be "the first" (1).
- when the test stimulus was presented at the highest of the nine magnitudes, it would cause more discomfort than the reference, so the answer to the question would be "the second" (2).
- there would be a transition magnitude above which the answer would be "2" and below which the answer would be "1". This magnitude was considered as the equivalent magnitude. So, for a given frequency and for one of the seven waveforms, it was expected that the results would be similar to the example shown in Table 7.7, with a clear limit between the magnitude range where the test was more uncomfortable and the range where the test was less comfortable, so an equivalent magnitude could be determined easily.

This method was considered in preference to the method of magnitude estimation because the question asked to subjects was simpler so the task would be easier, while still providing the sufficient information to determine the equivalent magnitude.

#### 7.4.1.2 Problems with the method

The results were not as easy to analyse as expected. In a number of cases, a test with a given magnitude was rated more uncomfortable than the reference, while at one higher magnitude it was rated less uncomfortable than the reference. This phenomenon was called 'inversions', which referred to a pair of magnitudes for which the higher magnitude was less uncomfortable than the reference, while the lower magnitude was more uncomfortable than the reference. In Table 7.8, examples of results with 0, 1, 4 and 12 inversions are shown (they are all results obtained during the preliminary experiment).

When inversions occurred, determining the equivalent magnitude became more complex. A method had to be chosen, for example taking the geometric mean of the lowest magnitude rated more uncomfortable than the reference and the highest magnitude rated less uncomfortable. However, as the number of inversions increased, this reliability of this method became more doubtful.

The maximum number of inversions for a waveform was 12, and in 25% of the cases, the number of inversions was 4 or more, which is enough to make the determination of the equivalent magnitude difficult (Table 7.8).

In addition to this phenomenon, in 25 of the 280 cases (12 subjects, 7 waveforms and 2 frequencies), a phenomenon of saturation occurred where the answer was the same for all magnitudes, making it impossible to determine the equivalent magnitude.

Table 7.7: Example of expected results with the method of constant stimuli at one frequency and with one magnitude. In that case, the equivalence magnitude is between the magnitude 3 and the magnitude 4.

| Magnitude of test stimulus | Answer | Signification |
|---|---|---|
| Magnitude 1 | "1" | $Test < Reference$ |
| Magnitude 2 | "1" | $Test < Reference$ |
| Magnitude 3 | "1" | $Test < Reference$ |
| Magnitude 4 | "2" | $Reference < Test$ |
| Magnitude 5 | "2" | $Reference < Test$ |
| Magnitude 6 | "2" | $Reference < Test$ |
| Magnitude 7 | "2" | $Reference < Test$ |
| Magnitude 8 | "2" | $Reference < Test$ |
| Magnitude 9 | "2" | $Reference < Test$ |

Table 7.8: Example of experimental results with 0, 1, 4 and 12 inversions.

| | 0 inversion | 1 inversion | 4 inversions | 12 inversions |
|---|---|---|---|---|
| Magnitude 1 | 1 | 1 | 1 | 2 |
| Magnitude 2 | 1 | 1 | 2 | 2 |
| Magnitude 3 | 1 | 1 | 1 | 1 |
| Magnitude 4 | 2 | 2 | 2 | 2 |
| Magnitude 5 | 2 | 1 | 2 | 1 |
| Magnitude 6 | 2 | 2 | 1 | 1 |
| Magnitude 7 | 2 | 2 | 2 | 2 |
| Magnitude 8 | 2 | 2 | 2 | 1 |
| Magnitude 9 | 2 | 2 | 2 | 2 |

#### 7.4.1.3 Choice of the method of magnitude estimation

The shortcomings of the method of constant stimuli exposed in Section 7.4.1.2 were related to the nature of the stimuli. The random motion and the inclusion of shocks made the comparisons difficult and added more inter-subject and intra-subject variability than if sinusoidal vibration had been used. In a number of cases, in particular when 'saturation' occurred, it was not possible to derive an estimate of the equivalent magnitude from the data.

The method of magnitude estimation was chosen instead, as it provided solutions to both problems mentioned in Section 7.4.1.2. The phenomenon of saturation could also occur with the method of magnitude estimation; as a result, the estimates for the nine magnitudes would all be greater than 100, or all be less than 100. However, a linear regression enables the experimenter to determine the equivalent magnitude by extrapolation (the equivalent magnitude is usually quite close to the bounds of the experimental range), whereas this is not possible with the method of constant stimuli. Similarly, performing a linear regression with magnitude estimates provides a way to average the results even when they show a large amount of variability, and overcome the problem of inversions.

### 7.4.2 The evaluation of transient motions in standards

Current standards advocate the use of the root-mean-square (r.m.s.) value of the frequency-weighted acceleration for evaluating the discomfort of standing people exposed to vibration in transport (i.e. the use of an $\lambda$ value of 2). However, it is suggested that when motions contain shocks or transients, the r.m.s. method might not be optimum. Two additional methods are advocated in ISO 2631-1 (1997): the vibration dose value, VDV (Equation 7.8; ISO 2631-1, 1997, Section 6.3.2, Equation 5), and the maximum transient vibration value (MTVV), which is the maximum value of the running r.m.s. value (Equation 7.9; ISO 2631-1, 1997, Section 6.3.1, Equations 2 and 4):

$$VDV = \left[\int_0^T a_w(t)^4 dt\right]^{1/4} \tag{7.8}$$

$$MTVV = \max\left\{\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w(t)^2 dt\right]^{1/2}\right\}_{t_0=\tau..T} \tag{7.9}$$

where:

- $a_w(t)$ is the weighted acceleration
- $T$ is the measurement period
- $\tau$ is the integration window size, with a recommended value of 1 s.

It is recommended in ISO 2631-1 (1997) to use one of these methods instead of the r.m.s. value when the crest factor of the motion is greater than 9; however, further in the standard, it is recommended to use additional methods when one of the two following criteria is exceeded (ISO 2631-1, 1997, Section 6.3.3, Equations 7 and 8):

$$\frac{MTVV}{r.m.s.} > 1.5 \tag{7.10}$$

$$\frac{VDV}{r.m.s. \times T^{1/4}} = \frac{r.m.q.}{r.m.s.} > 1.75 \tag{7.11}$$

In the present experiment, the motion stimuli were selected for their r.m.q./r.m.s. ratio rather than their crest factor, but motions with a higher r.m.q./r.m.s. ratio also have higher crest factors. Table 7.9 shows the mean values (across subjects) of the crest factors and the ratios defined in Equations (7.10) and (7.11) for the motions used in the current experiment. Because the test motions were of short duration, the crest factors were much less than 9 (the greatest crest factor was 5.0). The criterion in Equation (7.11) was also not exceeded, as the r.m.q./r.m.s. ratio was always less than 1.7. However, the criterion in Equation (7.10) was exceeded for most of the motions, implying the r.m.s. value might be expected to underestimate the discomfort of some of the motions, notably those with higher crest factors, and suggesting the MTVV method might be more appropriate.

Table 7.9: Arithmetic mean across subjects, magnitudes and directions of the characteristics of the seven different waveforms(A to G).

| Waveform | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| r.m.q./r.m.s. | 1.19 | 1.28 | 1.36 | 1.44 | 1.52 | 1.6 | 1.68 |
| Mean crest factor for 1-Hz motions | 1.9 | 2.3 | 2.4 | 2.6 | 2.9 | 3.1 | 3.3 |
| Mean crest factor for 8-Hz motions | 1.7 | 2.9 | 3.2 | 3.7 | 4.0 | 4.5 | 5.0 |
| Mean MTVV / r.m.s. ratio for 1-Hz motions | 1.3 | 1.6 | 1.7 | 1.7 | 1.9 | 2.0 | 2.1 |
| Mean MTVV / r.m.s. ratio for 8-Hz motions | 1.2 | 1.4 | 1.5 | 1.6 | 1.6 | 1.7 | 1.8 |

British Standard BS 6841 (1987) advocates the use of r.m.s. values for evaluating vibration when the crest factor is less than 6. If the crest factor is greater than 6 or the vibration contains occasional high peak values, the root-mean-quad (r.m.q.) method is recommended. None of the motions used in this experiment had a crest factor greater than 6, although it could be argued that some contained occasional high peak values.

### 7.4.3 Comparison of averaging method and MTVV methods

The optimal $(\lambda, \tau)$ pairs for each direction and frequency are shown in Figure 7.6 together with the pairs corresponding to r.m.s., r.m.q., and MTVV ($\tau$=1 s) methods. For 8-Hz vibration, the r.m.q. method and the MTVV method with $\tau$=1 s are both close to the curves, suggesting they could both provide satisfactory methods for evaluating 6-s periods of 8-Hz vibration. For 1-Hz vibration, the fourth power exponent in the r.m.q. is slightly too high and a window size greater than 1 s is required for the MTVV. The optimal window size is approximately 3 s for 1-Hz vibration and around 1.5 s for 8-Hz vibration (Table 7.6). With a fixed duration stimulus, reducing the window size in the MTVV method has the same effect as increasing the power in a ,ethod which integrates the acceleration time signal over the entire measurement period and relates the result to the duration: both emphasise the peaks in the motion.

The present study with 6-s stimuli found that the MTVV method could be made to provide a satisfactory prediction of the discomfort of standing people exposed to 6-s stimuli; however, since the integration time was highly dependent on the frequency, this will be difficult to implement in an evaluation method. Furthermore, the method is unlikely to work well with long duration stimuli, as the optimal integration time may vary with the stimulus duration. Also, the method implies that stimuli outside the integration period giving the greatest value will make no contribution to discomfort. This is contrary to expectations and the use of this method would allow vibration magnitudes to be increased at all periods other than during the worst part of the worst transient without increasing the estimation of discomfort.

Spång (1997) advocated the use of the MTVV method with an integration time of 1 s. This was based on a laboratory study where seated subjects were presented with 50 motions of duration 8 s and asked to rate the discomfort caused by each of them. The motions were vertical vibration recorded in industrial vehicles and contained shocks of various lengths. The MTVV ($\tau$=1 s) of the motions had the best correlation with the reported discomfort values (0.97, Spearman), compared to a whole range of methods including peak values, and $f_{\lambda,\tau}$ functions with $(\lambda, \tau)$ equal to (2,8 s) (i.e. r.m.s.), (4, 8 s) (i.e. r.m.q.) and (4, 1 s) . The correlation with the r.m.q. values was also high (0.91). No exponent between 2 and 4 or integration times between 1 s and 8 s were tested. The VDV method was equivalent to the r.m.q. method since all motions had the same duration.

The conclusion of that study is limited to the single event shocks of the type experienced close to the operator of mobile machinery, and the frequency content of the shock was not specified. From example motions shown in the article, the motions seem to be dominated by high frequencies. If the main frequency of the shocks was close to 8 Hz, the conclusion is consistent with the finding of the present study where the MTVV method with $\tau$=1 s was a satisfying choice for 8-Hz vibration.

Ruffell and Griffin (1995) reached a contrary conclusion after conducting a laboratory study where subjects were exposed to artificial stimuli made of an 80-s background vibration and an added transient sinusoidal vibration of frequency 1 Hz or 2 Hz and various durations between 1 and 60 s. The MTVV was not found appropriate for practical use as the integration time would have to be adjusted depending on the typical duration of the shocks. In the study by Spång (1997), the stimuli might all have had similar shock durations. Ruffel and Griffin (1995) also pointed out that although the r.m.s. values had a good correlation with reported values, the r.m.s. method was not appropriate for practically comparing motions with different duration. The VDV was found to solve this problem, because it takes the duration of the motion into account. In the present study, all stimuli had the same duration so it did not allow a choice between $rm_\lambda$ values (Equation 7.12) and $VD_\lambda$ values (Equation 7.14). For example, the VDV or the r.m.q. method would provide identical results.

The results of the present study also suggest an $rm_\lambda$ method (Equation 7.12) will tend to be slightly better than the MTVV method (Section 7.3.3), in addition to being easier to compute. For those reasons, an $rm_\lambda$ method is preferable to a MTVV method:

$$rm_\lambda = f_{\lambda,6s} = \left[\frac{1}{T}\int_0^T |a(t)|^\lambda dt\right]^{1/\lambda} \tag{7.12}$$

If such a method were to be used, the optimal $\lambda$ value would be around 3 for 1 Hz vibration and around 3.5 for 8-Hz vibration (Table 7.5).

### 7.4.4 Comparison with previous work

The discomfort caused by short-duration sinusoidal vertical vibration of seated subjects increases with increasing duration of vibration, with a time-dependency of the following form (Griffin and Whitham, 1980):

$$\log(a_1) = \log(k_1) - A\log(t_1) \tag{7.13}$$

where $a_1$ is the magnitude needed for a stimulus of duration $t_1$ to cause an equivalent discomfort to the reference stimulus, and $k_1$ and $A$ are constants. This implies that the discomfort caused by vibration is proportional to a vibration dose of the following form:

$$VD_\lambda = \left[\int_0^T |a(t)|^\lambda dt\right]^{1/\lambda} \tag{7.14}$$

where $\lambda$ is a constant exponent and $\lambda = \frac{1}{A}$ .

When comparing motions of equal duration, this is equivalent to using the $rm_\lambda$ method (Equation 7.3). The values corresponding to $\lambda$ in the study by Griffin and Whitham (1980) were 3.5, 2.9, 2.4, and 2.2 for 4 Hz, 8 Hz, 16 Hz, and 32 Hz vibration, respectively. The value found for 8-Hz vibration (i.e., 2.9) is similar to the results of the present study, where an optimal value for $\lambda$ of about 3.5 was found. However, the optimal exponent decreased with increasing frequency from 4 to 32 Hz, whereas the opposite was observed with the 1 Hz and 8 Hz frequencies in the present experiment. However, constant duration stimuli (i.e. 6 s) were used in the present experiment whereas Griffin and Whitham (1980) investigated variable durations from 4 s to 32 s.

In a related experiment, the discomfort caused by stimuli comprising different numbers of 8 Hz bumps superimposed on a background 8-Hz vibration was investigated (Griffin and Whitham, 1980). The complex motions contained 1, 2, 4, 8, or 16 bumps, with an overall duration of 10 seconds and the same r.m.s. magnitude (Figure 7.8). As the number of bumps increased, the crest factors of the motions decreased. The magnitude of the sinusoidal reference vibration equivalent in discomfort to each of the five complex motions was determined and compared with predictions based on the hypothesis that the discomfort is proportional to the $rm_{\lambda}$ value of the motion (Equation 7.3). The hypothesis was verified, and the results showed that $\lambda = 3$ when the reference stimulus was presented after the test stimulus, and $\lambda = 4$ when the reference stimulus was presented before the test stimulus, which is consistent with the results of the present study, where the optimal value for $\lambda$ was around 3.5 with 8-Hz vibration, presenting the reference stimulus before the test stimulus.

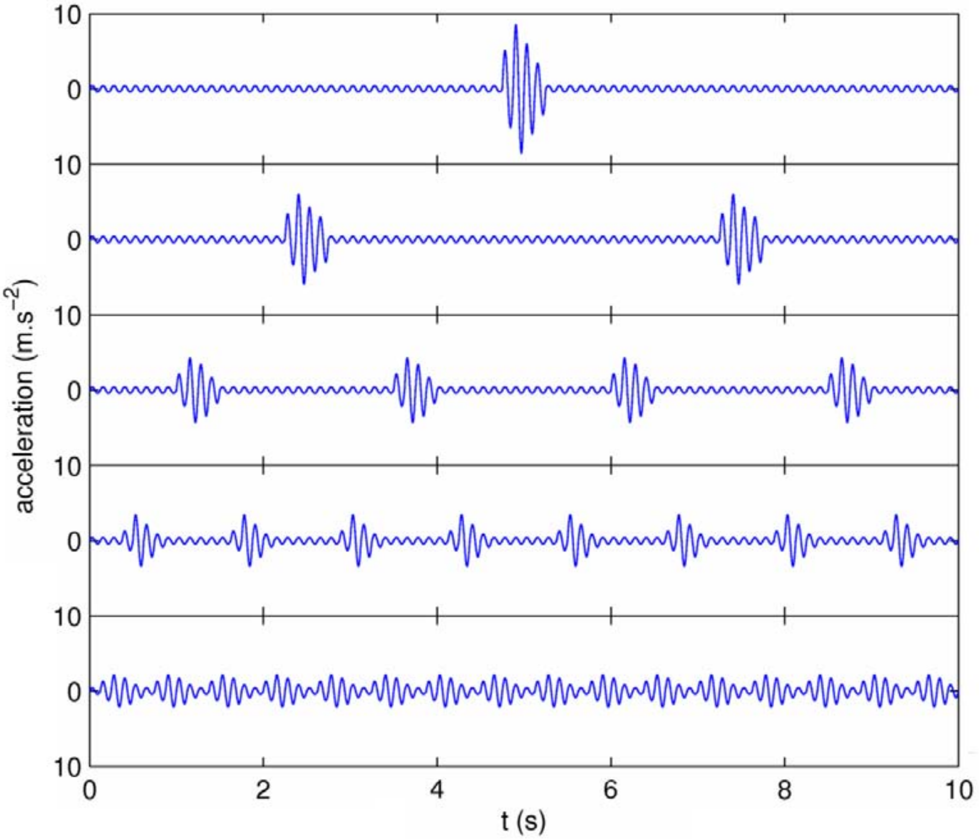


Figure 7.8: The five complex test motions used by Griffin and Whitham (1980): 1, 2, 4, 8, and 16 bumps. All motions have the same r.m.s. value.

The discomfort caused by vibration stimuli containing 1, 2, 4, 8, or 16 shocks added to a background random vibration was investigated by Howarth and Griffin (1991). The five waveforms were presented at magnitudes corresponding to constant $VD_4$ (i.e., VDV or r.m.q.), and at magnitudes corresponding to constant $VD_2$ (i.e. constant r.m.s.) as defined in Equation (7.14). It was found that when the $VD_2$ was held constant, the discomfort increased as the crest factor increased, suggesting the $VD_2$ dose underestimated the discomfort of more peaky motions. When the $VD_4$ was held constant, the discomfort was approximately constant, suggesting that a method with an exponent of 4 was more appropriate than a method with an exponent of 2, and that r.m.s. value underestimated the discomfort of motions with higher crest factors.

These previous studies of the discomfort of seated people exposed to transients appear reasonably consistent with the present studies of the discomfort of standing people.

### 7.4.5 Optimal evaluation method

The optimal $\lambda$ value seems to depend on frequency: for the standing subjects in the present study $\lambda$ was around 3 for 1-Hz vibration and around 3.5 for 8-Hz vibration (see Table 7.5). This suggests that whereas r.m.s. values underestimate the discomfort of motions containing transients, r.m.q. values tend to slightly overestimate the discomfort caused by transients (depending on the frequency). The use of both methods will assist the identification of transients causing discomfort and the minimisation of vibration discomfort. A more accurate estimation will be obtained by using an $rm_\lambda$ method. The optimal $\lambda$ value might depend on the frequency, so if the vibration contains several frequencies of vibration, it might be necessary to take an average of the recommended values. In particular, if the vibration includes frequencies between 1 and 8 Hz, an exponent of 3.25 might be optimal. If the range of frequencies is broader, for example 0.5 to 16 Hz, a $\lambda$ value in the range 3-3.5 should provide a good average. The practical value of 3 can be used.

### 7.4.6 The effect of duration

In the present study, all motions had the same duration. As a consequence, the adequacy of the $rm_\lambda$ (an averaging method) could not be compared with the adequacy of the use of a vibration dose $VD_\lambda$, which is cumulative. This means that the present results may show that the $rm_3$ method is optimal or that the $VD_3$ method is optimal but does not make it possible to decide between the two methods.

According to the studies by Howarth and Griffin (1991) and Ruffell and Griffin (1995), averaging methods are not appropriate for evaluating vibration of different duration, as the discomfort estimate could be artificially decreased if the recording period around a shock is increased. This suggests that the evaluation of vibration containing transient motions should be conducted by calculating the $VD_3$ dose value:

$$VD_3 = \left[\int_0^T |a(t)|^3 dt\right]^{1/3} \tag{7.15}$$

### 7.4.7 Conclusion

The discomfort caused by short duration (i.e. 6-second) vibration may be predicted using an $rm_\lambda$ method:

$$rm_\lambda = \left[\frac{1}{T}\int_0^T |a(t)|^\lambda dt\right]^{1/\lambda} \tag{7.16}$$

The optimal value of $\lambda$ may depend on the frequency. For the practical evaluation of vibration that may contain transient vibration, it can be helpful to evaluate the r.m.s. method (which will underestimate discomfort caused by transients) and the r.m.q. method (which will overestimate the discomfort caused by transients). For a more accurate estimate of the discomfort caused by vibration, the $rm_\lambda$ method may be used, with $\lambda$ being chosen equal to 3.0 for vibration in the frequency range 0.5 to 16 Hz. If stimuli of different duration are to be compared, the corresponding dose value may be more appropriate, although this was not investigated in the present study:

$$VD_3 = \left[ \int_0^T |a(t)|^3 dt \right]^{1/3} \tag{7.17}$$

# Chapter 8

# Predicting the discomfort caused by tri-axial vibration

## 8.1 Introduction

In Chapter 4, 5, 6 and 7, the effects of characteristics on the vibration on discomfort (frequency, magnitude, posture and supports, waveform, direction) were investigated in order to construct a model for predicting the discomfort of standing people exposed to vibration in the fore-and-aft, lateral or vertical direction. However, in usual exposure conditions, the vibration of the floor is never in a single direction, and consists of components in the three axes of translation and the three axes of rotation. Therefore, it is necessary to know how the discomfort caused by each of the components is combined, and to establish a model of the discomfort of multi-axis vibration.

In International and British Standards ISO 2631-1 (1997) and BS 6841 (1987), the method of the root-sum-of-squares is recommended for the evaluation of multi-axis vibration. Previous studies, for example by Fairley and Griffin (1988), Griffin and Whitham (1977), Griefahn and Bröde (1999) and Mistrot at al. (1990) suggested that this method is suitable for the evaluation of dual-axis sinusoidal vibration of seated people. The experiment presented in this Chapter was designed to determine a method for predicting the discomfort of tri-axial random vibration, $\psi_{total}$, from the discomfort of its single-axis components, $\psi_x$, $\psi_y$ and $\psi_z$. It was hypothesized that this could be achieved using a power summation function, similar to the root-sum-of-squares:

$$\psi_{total} = ({\psi_x}^{\alpha} + {\psi_y}^{\alpha} + {\psi_z}^{\alpha})^{\frac{1}{\alpha}} \tag{8.1}$$

Based on the results of the experiment, optimal values for the exponent $\alpha$ were determined, and the resulting model was compared with a model based on the masking theory similar to the model presented in Section 2.5.1.1 of the literature review.

## 8.2 Method

### 8.2.1 Motions

During an experimental session, subjects were exposed to vibration stimuli with components in the three translational directions: fore-and-aft, lateral and vertical. Motion stimuli were always presented in pairs; the first motion was called the reference motion, and the second motion, the test motion.

All vibration stimuli were 6 seconds long. All single-axis components of vibration stimuli were octave-band random motions of centre frequency either 1 Hz or 4 Hz. Within a pair of stimuli, all components of the reference and the test motions had the same frequency. The reference motion was composed of fore-and-aft, lateral, and vertical vibrations. The magnitude of each component is indicated in the first row in Tables 8.1 (1 Hz) and 8.2 (4 Hz). At each of the two frequencies, the reference motion was the same exact waveform throughout the whole experiment, and for all subjects. The test stimuli were composed of fore-and-aft, lateral, and vertical vibrations. In each direction, the magnitude was one of the five values indicated in Tables 8.1 (1 Hz) or 8.2 (4 Hz) for the corresponding direction. As shown in Tables 8.1 and 8.2, the magnitude in one or two of the directions could be zero, in which case the test motion was respectively dual-axis or single-axis. However in most cases, it was a tri-axial vibration. All combinations of the five magnitudes used in each of the three directions were presented as test stimuli, except the (0,0,0) combination; that means 124 (i.e. $5 \times 5 \times 5 - 1$) test motions were presented to each subject for both frequencies. In each direction and for each magnitude, the same exact waveform was used throughout the whole experiment, and for all subjects. At different magnitudes, different random waveforms were used.

The vibration magnitudes were chosen, based on the results of the experiments reported in Chapters 4 (where the effect of frequency was investigated) and 5 (where the effect of direction was investigated), so that at both frequencies and in all directions, they caused approximately equivalent discomfort.

In total, 248 vibration pairs were presented to each subject in a fully randomized order over two sessions. During each session, 124 vibration stimuli were presented, including 1-Hz and 4-Hz motions.

Table 8.1: Magnitudes of motions for 1-Hz vibration (all magnitudes are in m.s$^{-2}$ r.m.s.).

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| Reference | 0.15 | 0.15 | 0.30 |
| Test magnitude 1 | 0 | 0 | 0 |
| Test magnitude 2 | 0.09 | 0.09 | 0.19 |
| Test magnitude 3 | 0.15 | 0.15 | 0.30 |
| Test magnitude 4 | 0.24 | 0.24 | 0.48 |
| Test magnitude 5 | 0.38 | 0.38 | 0.75 |

Table 8.2: Magnitudes of motions for 4-Hz vibration (all magnitudes are in m.s$^{-2}$ r.m.s.).

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| Reference | 0.30 | 0.30 | 0.20 |
| Test magnitude 1 | 0 | 0 | 0 |
| Test magnitude 2 | 0.19 | 0.19 | 0.13 |
| Test magnitude 3 | 0.30 | 0.30 | 0.20 |
| Test magnitude 4 | 0.48 | 0.48 | 0.32 |
| Test magnitude 5 | 0.75 | 0.75 | 0.50 |

### 8.2.2 Procedure

As explained in Section 8.2.1, a total of 248 pairs of vibration were presented to each subject. These stimuli were presented in a randomized order (the random order was different for each subject) over two sessions.

After a pair of stimuli was presented, subjects were asked to estimate the discomfort caused by the test stimulus using the method of magnitude estimation (Section 3.4.1), by providing a number reflecting the discomfort caused by the test stimulus assuming the discomfort of the reference was 100. The vibration pair could be repeated if the subjects were unsure of their answer.

### 8.2.3 Equipment

The motions were produced using a six-axis motion simulator (Figure 8.1). The simulator can generate motions including fore-and-aft, lateral, vertical, pitch, roll and yaw, with a maximum displacement range of ±250 mm in the fore-and-aft and lateral directions, and ±500 mm in the vertical direction. The simulator was controlled by a Pulsar Digital Controller (Servotest Systems, Egham, UK). The motion stimuli were generated in Matlab (version R2009a) using the Matlab Toolbox HVLAB HRV (version 1.1) developed by the Human Factor Research Unit (University of Southampton).

Figure 8.1: Photograph and model of the safety frame mounted on the 6-axis motion simulator.

The vibration of the platform was monitored using Setra 141A capacitive accelerometers secured to the table of the simulator. The signals from the transducers were sampled by a Pulsar Digital Controller software at 256 samples per second after low pass filtering at 64 Hz. The performance of the simulator in terms of distortion and cross-axis coupling are reported in Chapter 3, Section 3.2.1.4.

### 8.2.4 Subjects

Sixteen healthy male university students and staff with median age 25 years (range 19 to 30 y), stature 178 cm (165 to 198 cm), weight 76 kg (50 to 104 kg) participated in the study. They attended two sessions lasting approximately 80 minutes. The characteristics of the subjects are listed in Table 8.3.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

### 8.2.5 Conditions and posture

The subjects wore socks but no shoes and wore a loose harness in case they should fall (Figure 8.1). The harness did not provide support or restrict movement when subjects stood as instructed. It was attached to an extruded aluminium frame secured to table of the vibrator.

The subjects maintained an upright posture, with their knees locked, and kept their eyes closed. Their feet were parallel and separated so that their lateral base of support (distance between the outer edges of their feet) was 350 mm, the median shoulder width for adult males (Pheasant, 1988).

Table 8.3: Physical characteristics of the subjects used in the experiment.

| Subject | Gender | Age | Height (cm) | Weight (kg) |
|---|---|---|---|---|
| 1 | M | 26 | 165 | 50 |
| 2 | M | 23 | 178 | 74 |
| 3 | M | 24 | 169 | 61 |
| 4 | M | 29 | 175 | 90 |
| 5 | M | 19 | 188 | 85 |
| 6 | M | 20 | 193 | 98 |
| 7 | M | 22 | 183 | 72 |
| 8 | M | 25 | 175 | 82 |
| 9 | M | 23 | 198 | 104 |
| 10 | M | 26 | 178 | 60 |
| 11 | M | 28 | 170 | 55 |
| 12 | M | 30 | 174 | 70 |
| 13 | M | 26 | 182 | 81 |
| 14 | M | 27 | 167 | 61 |
| 15 | M | 25 | 178 | 80 |
| 16 | M | 24 | 185 | 78 |
| Median | / | 25 | 178 | 76 |

The subjects wore headphones delivering broadband noise at 65 dB(A). The headphones also provided some acoustic isolation from external noises, and this was found sufficient to mask noises produced by the simulator when generating motions (Section 3.3.4).

### 8.2.6 Analysis

#### 8.2.6.1 The discomfort of the single-axis components

Out of the 124 test motions presented at each frequency, some were single-axis motions (this happened when the magnitude in two of the directions was zero). When such motions were presented, the discomfort estimate provided by the subject was equal to the discomfort caused by the single-axis motion. Therefore, after completion of the experiment, for each subject, the discomfort caused by all twelve single-axis components used to construct the multi-axis test stimuli (i.e. four magnitudes in each of three axes) was known.

#### 8.2.6.2 Assessment of summation methods

Twelve of the 124 test stimuli were single-axis motions, so 112 of the stimuli were dual-axis or tri-axial motions. For each subject, the discomfort caused by all multi-axis motions was known after the magnitude estimation was performed. This discomfort could also be estimated from the discomfort caused by the three single-axis components (also known for each subject, as explained in Section 8.2.6.1) using, for example, the method of the root-sum-of-squares. To determine whether this method was appropriate, for each subject, the measurements of discomfort obtained with the 112 multi-axis motions were compared with the prediction from the discomfort of the single-axis components using the Wilcoxon signed-rank test. If the predictions were found to be significantly greater than the measurements, it was concluded that the method that was used (in this example, the root-sum-of-squares) overestimated the discomfort of multi-axis motions. Conversely, if the predictions were significantly less than the measurements, it was concluded that the method underestimated the discomfort of multi-axis motions.

#### 8.2.6.3 Individual optimized power summation method

It was hypothesized that the discomfort of multi-axis vibration could be predicted from the discomfort of its single-axis components with a power summation method:

$$\psi_{total} = ({\psi_x}^{\alpha} + {\psi_y}^{\alpha} + {\psi_z}^{\alpha})^{\frac{1}{\alpha}} \tag{8.2}$$

where:

- $\psi_{total}$ is the discomfort of the multi-axis motion
- $\psi_x$ is the discomfort of the fore-and-aft component when presented alone
- $\psi_y$ is the discomfort of the lateral component when presented alone
- $\psi_z$ is the discomfort of the vertical component when presented alone
- $\alpha$ is an exponent to determine

When $\alpha = 1$, the discomfort of the multi-axis motion is predicted by the linear sum of the discomfort in all direction:

$$\psi_{total} = \psi_x + \psi_y + \psi_z \tag{8.3}$$

It was hypothesized that this prediction method generally overestimates the multi-axis discomfort. When $\alpha = \infty$, the discomfort of the multi-axis motion is predicted by the discomfort of the most uncomfortable component (this is the ‘worst component’ method):

$$\psi_{total} = \max(\psi_x, \psi_y, \psi_z) \tag{8.4}$$

It was hypothesized that this prediction method generally underestimates the discomfort of multi-axis components.

If the hypotheses that the predictions are greater than the measurements with $\alpha = 1$ and less than the measurements with $\alpha = \infty$ are true, there must be values of $\alpha$ in the range $[1, \infty]$ for which the predictions obtained with Equation (8.2) are not significantly different from the measurements. Such values of $\alpha$ were defined as suitable exponents, and were calculated for each subject, when applicable. A range of $\alpha$ values for which the prediction were not different from the measurements ($p > 0.05$) was determined; in this range, the value for which the $p$ value was equal to 1 and the predictions changed from being (non-significantly) greater than the measurements to being smaller than the measurements, was considered to be the optimal value.

#### 8.2.6.4 Global optimal summation method

Because of inter-individual differences, there might not be a single prediction method suiting all passengers or subjects. The objective was therefore to determine a method which provides an average estimate of the discomfort of multi-axis vibration, and which averages out the inter-subject differences. For this purpose, the measurements and predictions of discomfort of the multi-axis stimuli obtained with all 16 subjects were pooled together, and the procedure described in Section 8.2.6.3 was repeated on the pooled data in order to determine the suitable and optimal $\alpha$ values for the whole sample of subjects.

The procedure used for the data analysis is summarized in Figure 8.2.

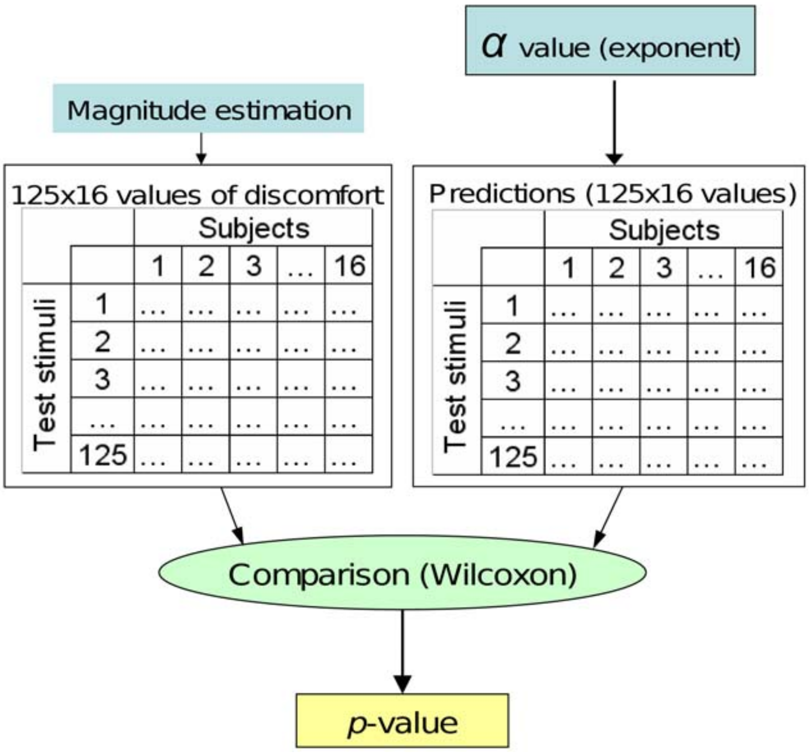


Figure 8.2: Summary of the data analysis procedure.

#### 8.2.6.5 Other prediction method: masking theory

Masking models have been used in the past for the evaluation of complex vibration, but also for the evaluation of dual-axis motion, for example by Griffin and Whitham (1977). In the case of a dual-axis motion, it is assumed that the effect of the secondary component is reduced because that component is masked by the main component (i.e. the component that causes most discomfort). So, in the summation procedure, the discomfort of the secondary component is multiplied by a masking coefficient comprised between 0 and 1. This method can be adapted in the case of tri-axial motions, so it may possible to predict the discomfort of the multi-axis motion with Equation (8.5):

$$\psi_{total} = \psi_1 + A\,\psi_{2,3} \tag{8.5}$$

where:

- $\psi_{total}$ is the predicted discomfort of the multi-axis vibration
- $\psi_1$ is the discomfort of the most uncomfortable component
- $\psi_{2,3}$ is the discomfort caused by the two secondary components
- $A$ is the masking coefficient, to be determined.

The discomfort of the two secondary components is essentially determined by the most uncomfortable of the two (of subjective magnitude $\psi_2$), as the effect of the smallest coefficient is reduced by the same masking effect. It is assumed that the masking coefficient is the same as in Equation (8.5) as the effect is similar:

$$\psi_{2,3} = \psi_2 + A\,\psi_3 \tag{8.6}$$

As a consequence:

$$\psi_{total} = \psi_1 + A\,\psi_2 + A^2\,\psi_3 \tag{8.7}$$

where:

- $\psi_{total}$ is the predicted discomfort of the multi-axis vibration
- $\psi_1$, $\psi_2$ and $\psi_3$ are the subjective magnitudes of, respectively, the most uncomfortable component, the second most uncomfortable component, and the least uncomfortable component.

If $A = 0$ (which means that the effect of any secondary component is completely masked by the main component), the model is equivalent to the worst component model, as shown in Equation 8.4, which is equivalent to Equation 8.2 with $\alpha = \infty$. This prediction method usually underestimate the discomfort caused by multi-axis vibration.

If $A = 1$ (which means that no masking is occurring), the discomfort is predicted by the linear sum of the discomfort of all components, as shown in Equation 8.3, which is equivalent to Equation 8.2 with $\alpha = 1$. This method usually overestimates the discomfort.

This suggests that a value of $A$ can be found in the range $[0, 1]$ for which there is no significant difference between the predictions and the reported discomfort of tri-axial motion stimuli. Such a value was determined in a similar way as the optimal exponent for the power summation method, as explained in Section 8.2.6.4, and the resulting method was compared with the power summation method.

## 8.3 Results

### 8.3.1 Worst component methods and linear sum

As explained in Section 8.2.6.3, it was hypothesized that the method of linear sum (Equation 8.3) overestimated the discomfort of multi-axis vibration, and that the method of worst component (Equation 8.4) underestimated the discomfort of multi-axis vibration. To test these hypotheses, the predictions from those two methods were compared with the reported discomfort of the multi-axis motion using the Wilcoxon signed rank test. The comparison was repeated for each subject, and at both frequencies. The results (the $p$-values and the direction of the differences) are reported in Table 8.4 (linear sum) and 8.5 (worst component). It appears that at both frequencies and for all subjects, the method of linear sum overestimated the discomfort ($p < 0.05$). The method of the worst component ($\alpha = \infty$) underestimated the discomfort significantly for 11 subjects at 1 Hz, and 14 subjects at 4 Hz (the cases where the difference was significant are marked with a star in Tables 8.4 and 8.5)

The results show that the methods of the linear sum ($\alpha = 1$) and the worst component ($\alpha = \infty$) are not appropriate because they, respectively, overestimate and underestimate the discomfort of multi-axis vibration. This can be observed in Figures 8.7 and 8.8 where the predictions obtained with $\alpha = 1$ and $\alpha = \infty$ are compared with the reported discomfort. This suggests that values of $\alpha$ can be found in the range $[1, \infty]$ for which the prediction matches the actual discomfort.

### 8.3.2 Individual optimal summation method

As shown in Section 8.3.1, for most subjects, the discomfort predictions were greater than the measurements for $\alpha = 1$, but less than the measurements for $\alpha = \infty$. Therefore, in

Table 8.4: Comparison of the predictions of discomfort obtained with the linear sum method (Equation 8.3) with the measurement. The $p$-value of the Wilcoxon test is reported, with the direction of the difference. (+): predictions were greater than measurements; (-): predictions were less than measurements. The cases where the difference was significant ($p < 0.05$) are marked with a star (*).

| Subject | 1 Hz | | 4 Hz | |
|---|---|---|---|---|
| | $p$ | Direction | $p$ | direction |
| 1 | 4e-20 | (+)* | 4e-20 | (+)* |
| 2 | 1e-19 | (+)* | 2e-18 | (+)* |
| 3 | 8e-20 | (+)* | 6e-19 | (+)* |
| 4 | 1e-11 | (+)* | 5e-18 | (+)* |
| 5 | 1e-8 | (+)* | 2e-17 | (+)* |
| 6 | 9e-20 | (+)* | 3e-19 | (+)* |
| 7 | 1e-19 | (+)* | 6e-20 | (+)* |
| 8 | 7e-20 | (+)* | 4e-20 | (+)* |
| 9 | 6e-20 | (+)* | 4e-19 | (+)* |
| 10 | 3e-17 | (+)* | 4e-15 | (+)* |
| 11 | 1e-19 | (+)* | 1e-19 | (+)* |
| 12 | 1e-6 | (+)* | 2e-15 | (+)* |
| 13 | 1e-19 | (+)* | 4e-18 | (+)* |
| 14 | 7e-9 | (+)* | 9e-19 | (+)* |
| 15 | 5e-19 | (+)* | 6e-20 | (+)* |
| 16 | 8e-19 | (+)* | 6e-18 | (+)* |

the range $[1, \infty]$, there should be a subrange of $\alpha$ values for which there is no significant difference.

In Figures 8.3 and 8.4 the $p$-values obtained by comparing the predictions with the measurements using the Wilcoxon signed-rank test are shown for $\alpha$-values in the range 1 to 12. For most of the subjects, there is a range of $\alpha$ values for which $p > 0.05$ (i.e. there is no significant difference between the predictions and the measurement). This was considered as the range of suitable $\alpha$ values for each subject, as explained in Section 8.2.6.3. These ranges are reported in Table 8.6. The optimal exponents (i.e. the values of $\alpha$ for which $p = 1$) are also reported for each subject.

The ranges of suitable $\alpha$-values are different for each subject, although for most of them the optimal value is between 2 and 4.

### 8.3.3 Global optimal summation method

As explained in Section 8.2.6.4, the data from all subjects were pooled together in order to determine a summation method that averages out inter-individual differences and can be used to predict the average discomfort of people exposed to multi-axis vibration.

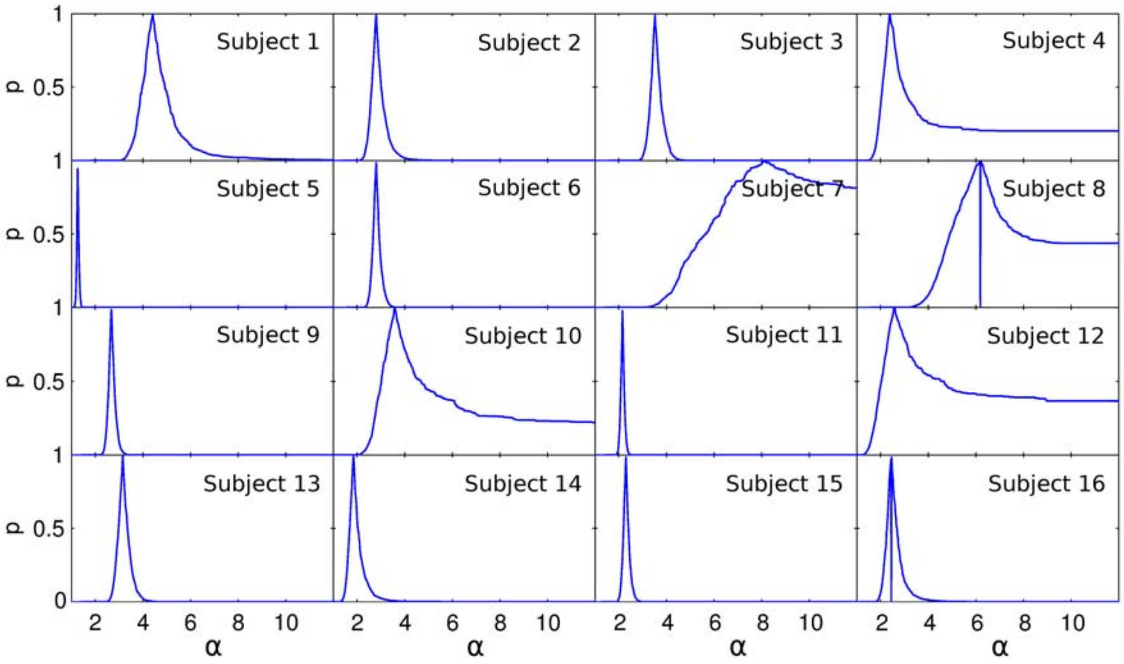


Figure 8.3: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 1-Hz vibration with the predictions using a power summation method (Equation 8.2), with values of $\alpha$ between 1 and 12.

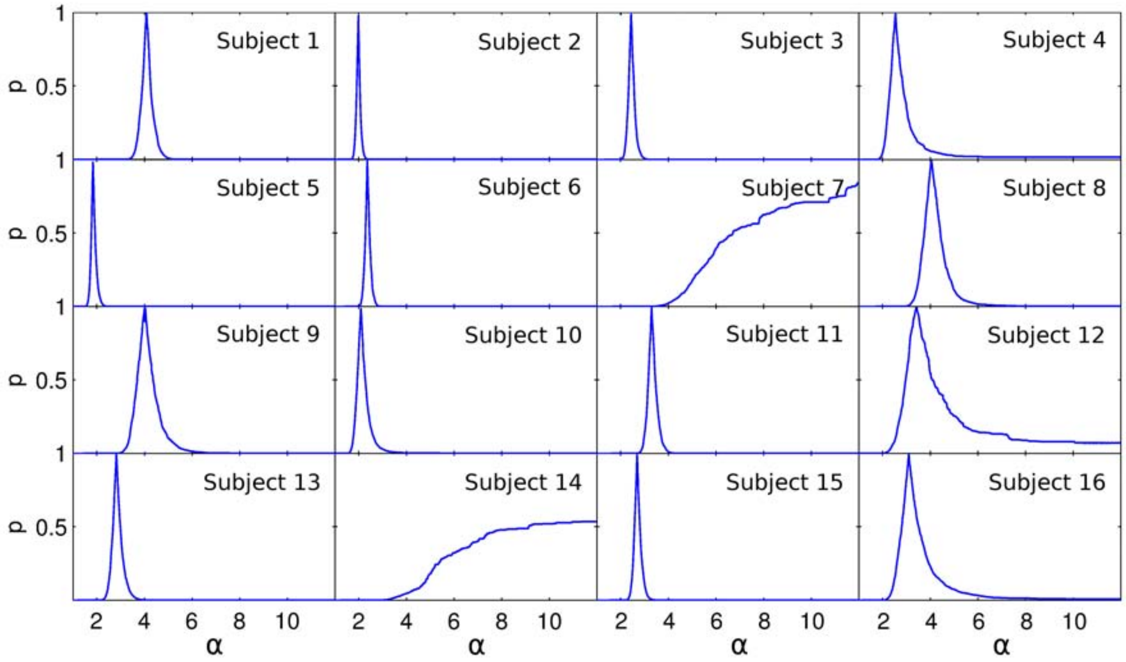


Figure 8.4: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 4-Hz vibration with the predictions using a power summation method (Equation 8.2), with values of $\alpha$ between 1 and 12.

Table 8.5: Comparison of the predictions of discomfort obtained with the worst component method (Equation 8.4) with the measurement. The $p$-value of the Wilcoxon test is reported, with the direction of the difference. (+): predictions were greater than measurements; (-): predictions were less than measurements. The cases where the difference was significant ($p < 0.05$) were marked with a star (*).

| Subject | 1 Hz | | 4 Hz | |
|---|---|---|---|---|
| | p | direction | p | direction |
| 1 | 1e-4 | (-)* | 8e-14 | (-)* |
| 2 | 4e-5 | (-)* | 1e-15 | (-)* |
| 3 | 7e-1 | (-)* | 2e-11 | (-)* |
| 4 | 0.17 | (-) | 5e-3 | (-)* |
| 5 | 4e-17 | (-)* | 5e-11 | (-)* |
| 6 | 8e-13 | (-)* | 2e-12 | (-)* |
| 7 | 0.49 | (-) | 0.54 | (-) |
| 8 | 0.18 | (-) | 1e-4 | (-)* |
| 9 | 2e-11 | (-)* | 3e-5 | (-)* |
| 10 | 0.19 | (-) | 1e-4 | (-)* |
| 11 | 4e-17 | (-)* | 6e-11 | (-)* |
| 12 | 0.27 | (-) | 1e-2 | (-)* |
| 13 | 1e-8 | (-)* | 7e-9 | (-)* |
| 14 | 2e-4 | (-)* | 0.78 | (+) |
| 15 | 2e-11 | (-)* | 9e-12 | (-)* |
| 16 | 1e-4 | (-)* | 9e-4 | (-)* |

For values of $\alpha$ between 1 and 4, the predictions of the discomfort of multi-axis stimuli obtained with Equation (8.2) were compared with the actual values of discomfort using the Wilcoxon signed-rank test. The $p$-values obtained with all values of $\alpha$ in the range [1,4] are shown in Figures 8.5 (1-Hz vibration) and 8.6 (4-Hz vibration).

For small values of the exponent $\alpha$ ($\alpha < 2.56$ at 1 Hz, $\alpha < 2.82$ at 4 Hz), the predictions were significantly greater than the measurements ($p < 0.05$). For greater values of $\alpha$ ($\alpha > 2.88$ at 1 Hz, $\alpha > 3.14$ at 4 Hz), the predictions were significantly less than the measured values ($p < 0.05$).

At both frequencies, a range of values could be found for $\alpha$ for which the predictions were not significantly different from the actual discomfort. These ranges of suitable $\alpha$ values are shown in Figures 8.5 and 8.6 as shaded areas, and are reported in Table 8.7.

The results show that values of $\alpha$ between 2.6 and 2.9 are suitable for 1-Hz vibration, and values of $\alpha$ between 2.8 and 3.1 are suitable for 4-Hz vibration. That suggests that values between 2.8 and 2.9 can be used to predict discomfort of multi-axis vibration at both frequencies.

Table 8.6: Ranges of suitable $\alpha$ values and optimal exponent for each subject.

| | Subject | Range of $\alpha$ values for which $p > 0.05$ | Optimal value |
|---|---|---|---|
| 1 Hz | 1 | 3.4 - 6.7 | 4.4 |
| | 2 | 2.3 - 3.7 | 2.8 |
| | 3 | 3.0 - 4.2 | 3.5 |
| | 4 | 1.7 - $\infty$ | 2.4 |
| | 5 | 1.2 - 1.4 | 1.3 |
| | 6 | 2.5 - 3.3 | 2.8 |
| | 7 | 3.8 - $\infty$ | 8.1 |
| | 8 | 3.8 - $\infty$ | 6.2 |
| | 9 | 2.4 - 3.1 | 2.7 |
| | 10 | 2.4 - $\infty$ | 3.6 |
| | 11 | 2.0 - 2.4 | 2.2 |
| | 12 | 1.5 - $\infty$ | 2.6 |
| | 13 | 2.7 - 3.9 | 3.2 |
| | 14 | 1.5 - 2.7 | 1.9 |
| | 15 | 2.0 - 2.7 | 2.3 |
| | 16 | 2.0 - 3.4 | 2.5 |
| 4 Hz | 1 | 3.6 - 4.7 | 4.1 |
| | 2 | 1.8 - 2.2 | 2.0 |
| | 3 | 2.2 - 2.8 | 2.4 |
| | 4 | 2.0 - 4.3 | 2.5 |
| | 5 | 1.6 - 2.2 | 1.8 |
| | 6 | 2.1 - 2.7 | 2.4 |
| | 7 | 4.3 - $\infty$ | 46.9 |
| | 8 | 3.3 - 5.4 | 4.0 |
| | 9 | 3.3 - 5.4 | 4.0 |
| | 10 | 1.7 - 2.8 | 2.1 |
| | 11 | 2.9 - 3.8 | 3.3 |
| | 12 | 2.4 - 18.3 | 3.4 |
| | 13 | 2.4 - 3.4 | 2.8 |
| | 14 | 4.1 - $\infty$ | 70 |
| | 15 | 2.4 - 3.1 | 2.7 |
| | 16 | 2.4 - 5.4 | 3.1 |

### 8.3.4 Comparisons between predictions and magnitude estimates

The predictions obtained with Equation (8.2) and $\alpha = 1$, 2, 2.85 and $\infty$ are compared with the actual discomfort values in Figures 8.7 (1-Hz vibration) and 8.8 (4-Hz vibration). The predicted discomfort is reported on the vertical axis, and the measured discomfort for the same multi-axis stimulus is reported on the horizontal axis. The line $y = x$ is also shown. Points located above that line represent multi-axis stimuli for which the discomfort was overestimated by the summation method. Conversely, points located below the line represent multi-axis stimuli for which the discomfort was underestimated by the summation

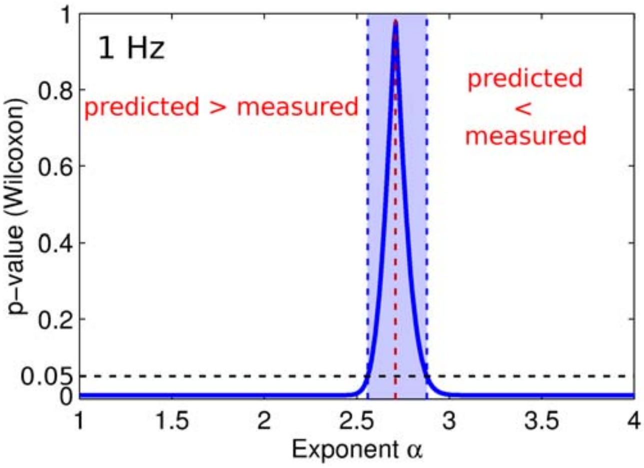


Figure 8.5: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 1-Hz vibration with the predictions obtained with all subjects using a power summation method (Equation 8.2), with values of $\alpha$ between 1 and 4. The shaded area is the range of $\alpha$ for which the predictions are not different from the measurements ($p > 0.05$).

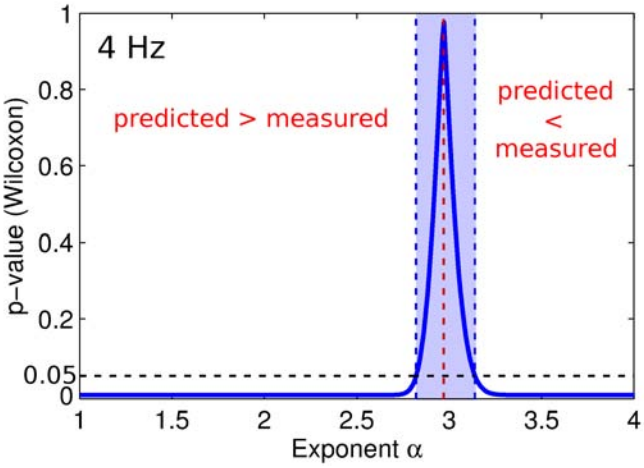


Figure 8.6: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 4-Hz vibration with the predictions obtained with all subjects using a power summation method (Equation 8.2), with values of $\alpha$ between 1 and 4. The shaded area is the range of $\alpha$ for which the predictions are not different from the measurements ($p > 0.05$).

method. It can be observed that when $\alpha = 1$ (linear sum), almost all stimuli are overestimated, and that when $\alpha = \infty$ (worst component), most stimuli are underestimated. When $\alpha = 2$ (root-sum-of-squares), more stimuli are overestimated than underestimated (there are more points located above the line than below). When $\alpha = 2.85$, it has been shown in Section 8.3.3 that the predictions are not significantly different from the measurements and it can be seen in Figures 8.7 and 8.8 that the line is in the middle of the data scatter, which means that the predictions globally fit the measurements.

Table 8.7: Suitable range of $\alpha$ values (for which $p > 0.05$) and optimal $\alpha$ value ($p = 1$) obtained with all subjective data, at 1 Hz and 4 Hz.

| | Suitable range | Optimal value |
|---|---|---|
| 1Hz | 2.6 - 2.9 | 2.7 |
| 4Hz | 2.8 - 3.1 | 3.0 |

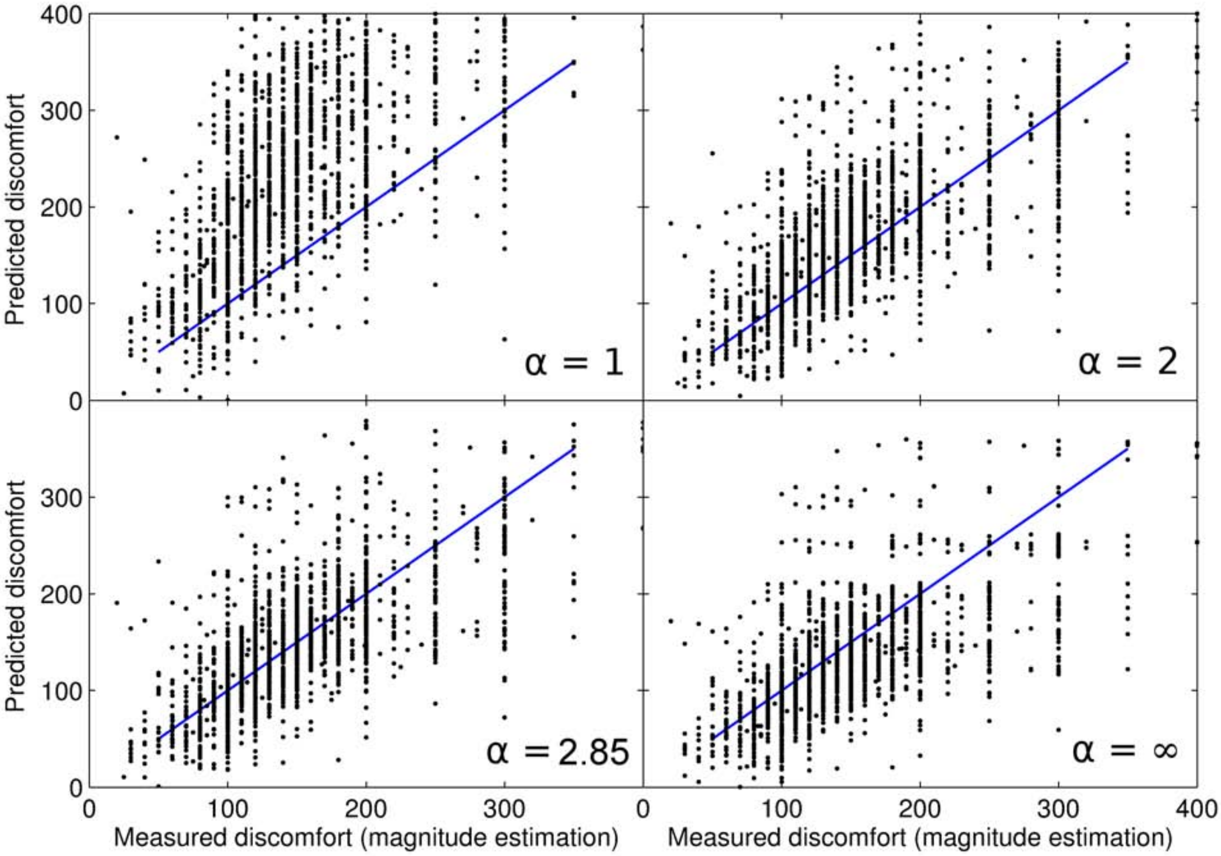


Figure 8.7: Comparison of the predicted discomfort of 1-Hz vibration obtained with power summation methods (Equation 8.2) with four different values of $\alpha$, and the measurements. The $y = x$ line is also shown.

### 8.3.5 Masking method

An alternative way of combining the discomfort of single-axis components is based on the masking model, as presented in Section 8.2.6.5:

$$\psi_{total} = \psi_1 + A\,\psi_2 + A^2\,\psi_3 \tag{8.8}$$

where:

- $\psi_{total}$ is the predicted discomfort of the multi-axis vibration

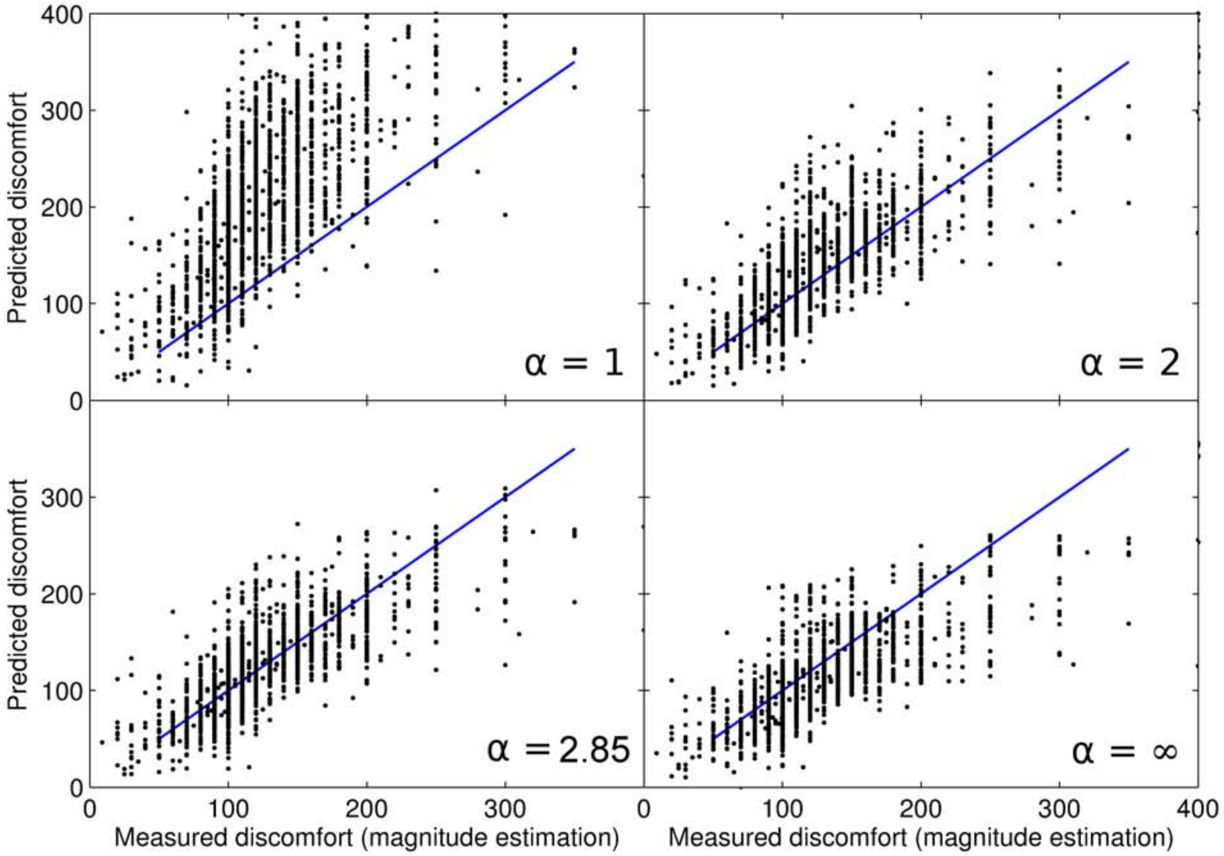


Figure 8.8: Comparison of the predicted discomfort of 4-Hz vibration obtained with power summation methods (Equation 8.2) with four different values of $\alpha$, and the measurements. The $y = x$ line is also shown.

- $\psi_1$, $\psi_2$ and $\psi_3$ are the subjective magnitudes of, respectively, the most uncomfortable component, the second most uncomfortable component, and the least uncomfortable component.
- $A$ is the masking coefficient, to determine.

For most subjects, when $A = 0$ (worst component method), the discomfort was underestimated, and when $A = 1$ (linear sum), the discomfort was overestimated, as shown in Section 8.3.1. In the range [0,1], values of the masking coefficient $A$ for which the prediction of the masking model were not significantly different ($p > 0.05$, Wilcoxon) from the reported discomfort were determined on the basis of pooled data and are shown as shaded areas in Figures 8.9 and 8.10.

It was found that $A = 0.19$ is a suitable value at both frequencies. Therefore, the discomfort of the tri-axial motions $\psi_{total}$ can be predicted with Equation (8.9):

$$\psi_{total} = \psi_1 + 0.19\,\psi_2 + 0.19^2\,\psi_3 \tag{8.9}$$

where $\psi_1$, $\psi_2$ and $\psi_3$ are the subjective magnitudes of, respectively, the most uncomfortable component, the second most uncomfortable component, and the least uncomfortable component.

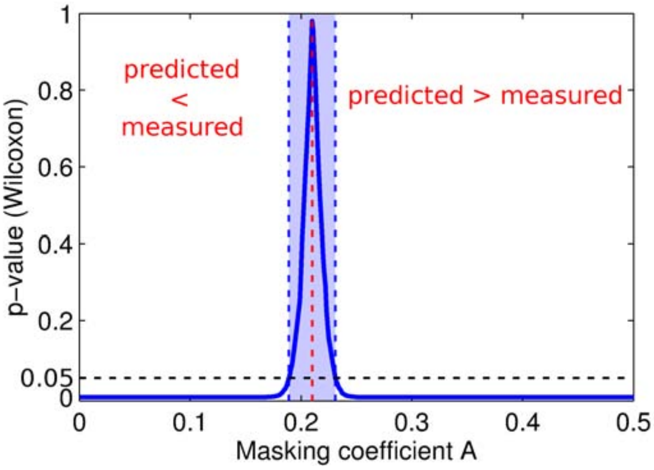


Figure 8.9: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 1-Hz vibration with the predictions obtained with all subjects using the masking model (Equation 8.8), with values of $A$ between 0 and 0.5. The shaded area is the range of $A$ for which the predictions are not different from the measurements ($p > 0.05$).

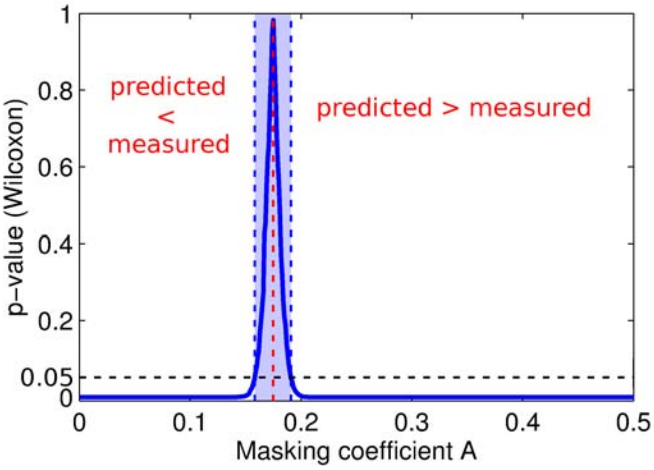


Figure 8.10: The $p$-value of the Wilcoxon signed rank test comparing the measured discomfort of 4-Hz vibration with the predictions obtained with all subjects using the masking model (Equation 8.8), with values of $A$ between 0 and 0.5. The shaded area is the range of $A$ for which the predictions are not different from the measurements ($p > 0.05$).

## 8.4 Discussion

### 8.4.1 The effect of phase

The discomfort caused by multi-axis vibration stimuli may not only depend on the magnitude of each component, but also on the phase of all components. For example, in the case of a dual-axis vibration consisting of sinusoidal components at the same frequency in two orthogonal directions, the phase lag between the two components determines whether the motion is linear (phase lag equal to 0°), circular (90°), or elliptical (other values of phase lag). As a consequence, the discomfort of a multi-axis motion may depend on the phase of each of the components. Griffin and Whitham (1977) found that when subjects were exposed to dual-axis (lateral and vertical) 3.15 Hz sinusoidal motion with a phase lag of either 0° or 90°, the discomfort caused by the linear motion was equivalent to the discomfort of the circular motion except in one case, where the difference was still less than 5%; it was therefore concluded that the effect of phase lag is negligible. Shoenberger (1987) investigated the discomfort of dual-axis motions with lateral and vertical sinusoidal components with frequencies 3.2, 5 and 8 Hz and phase lags 0°, 90°, 180° and 270°. The phase lag had no effect on discomfort. In similar conditions, however, Shoenberger (1988) found that the discomfort depended on the phase lag when the motion had fore-and-aft and vertical components, although the effect was limited. From those studies, it can be considered that the discomfort of seated people exposed to dual-axis vibration does not significantly depend on the phase lag between the two components.

In the present work, the conditions are different from the conditions of the previous studies, as the subjects were standing and exposed to tri-axial vibration, so the phase lags may have had an effect on discomfort. However the effect of phase lag with three components could be very complex, and this effect was not the focus of this study which aimed at obtaining an evaluation method applicable in the general case, so the choice of vibration stimuli was such that the phase lag between components varied to a large extent over the duration of the test stimuli.

The single-axis components of the vibration stimuli were independent octave-band random vibrations. In Figure 8.11, two 1-Hz octave-band random motions presented simultaneously, respectively, in the fore-and-aft and the lateral direction are shown. The variation of phase lag between the two motions was also estimated. To do so, a linear interpolation method was used, where the phase of each signal was estimated at each time increment from the time elapsed since the last peak and the time remaining until the next peak. The difference between the phases of the two signals was then calculated and is shown in Figure 8.11. For example, at $t = 0.5$ s, the phase lag is 0°, and the signals are in-phase: they both reach a maximum simultaneously. Conversely, at $t = 3.5$ s, the phase lag is 180°, and the signals are out-of-phase. Indeed, at $t = 3.25$ s, the lateral vibration reaches a maximum whereas the fore-and-aft vibration reaches a minimum.

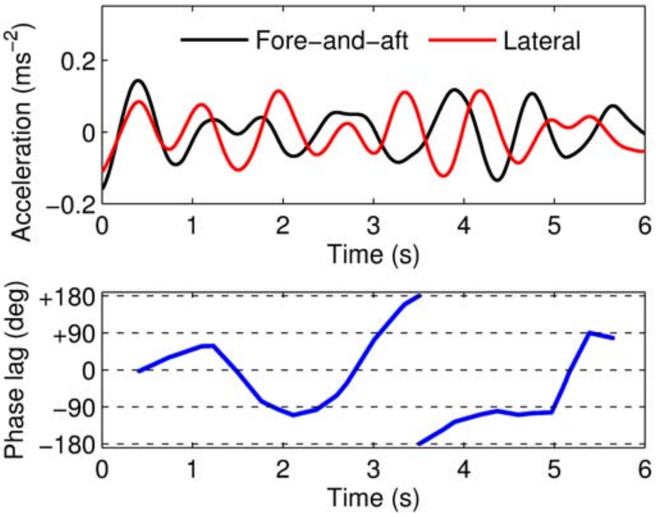


Figure 8.11: An example of two 1-Hz octave-band random signals, and the evolution of the phase lag between them over 6 seconds.

The variations of the phase lag in Figure 8.11 show that over 6 seconds, the phase lag between two 1-Hz octave-band random motions varies over the whole range of phase lags from −180° and +180°. This suggests that, in the experiment, any effect of phase was averaged over the duration of the test stimuli, which was six seconds. A similar study was conducted with 4-Hz vibrations, and an example is shown in Figure 8.12. As expected, the phase varies faster than with 1-Hz vibration, so the phase lag between the two components covers the whole range of values from −180° to +180° several times.

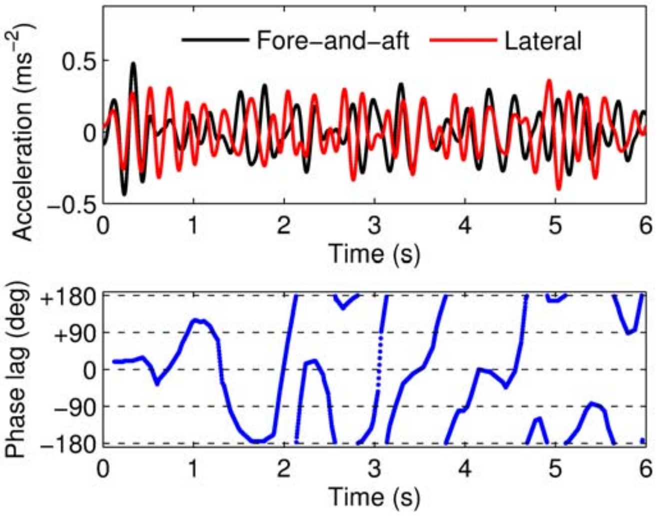


Figure 8.12: An example of two 4-Hz octave-band random signals, and the evolution of the phase lag between them over 6 seconds.

As a consequence, if the discomfort of multi-axis vibration depends on the phase relation between the components, the procedure resulting of the analysis is an average, and might slightly overestimate the discomfort of tri-axial motion stimuli with a particular phase relationship, and underestimate the discomfort of stimuli with another particular phase relationship; but for a typical vibration exposure, provided the phase relationships vary with time over the duration of the vibration motion (which normally happens), the summation procedure will be unbiased.

## 8.4.2 The effect of the relative magnitudes of components

### 8.4.2.1 The heterogeneity factor

Some of the test stimuli consisted of three components of equivalent subjective magnitude, while in some other stimuli, the main component was much more uncomfortable than the other components. This characteristic may influence the choice of a prediction method, and, for example, a particular masking coefficient might be suitable for specific relative magnitudes between components. Also, the optimal methods determined in Section 8.3 were constructed so that there was no average difference between predictions and measurements, but they may, for example, underestimate homogeneous stimuli but overestimate highly heterogeneous stimuli; when analyzing all stimuli together, this would appear as being unbiased, although the method would be biased if such was the case. If this was the case, the optimal parameter values would result from the particular choice of stimuli. So, the effect of the relative magnitudes of the components on the accuracy of the predictions was investigated.

The motion stimuli were characterized by their heterogeneity $H$ which was defined as the ratio of the discomfort caused by the worst component to the mean of the discomfort caused by the three components:

$$H = \frac{\max(\psi_x, \psi_y, \psi_z)}{\frac{1}{3}(\psi_x + \psi_y + \psi_z)} \tag{8.10}$$

If the three components were equivalent, $H$ was close to 1. If two of the components were negligible compared to a dominant one, $H$ was close to 3. For any triaxial motion, $H$ was always between those two extreme values (between 1 and 3). Examples of tri-axial motions with heterogeneity 1, 1.5, 2, 2.5 and 3 are shown in Figure 8.13.

### 8.4.2.2 The effect of heterogeneity

In Figures 8.14 and 8.15, the (logarithmic) errors between the predictions of the power summation model, with four different values of the exponent $\alpha$, and the measured discomfort are shown as a function of the heterogeneity $H$. Additionally, the test stimuli were (arbitrarily) sorted in four groups according to their heterogeneity ($1 < H < 1.5$; $1.5 < H < 2$; $2 < H < 2.5$; $2.5 < H < 3$) and the median error and interquartile range were calculated for each group.

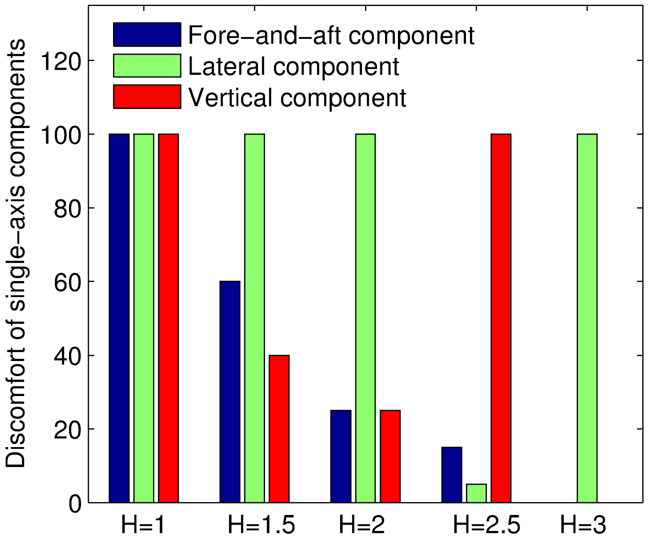


Figure 8.13: Examples of tri-axial motions with heterogeneity of 1, 1.5, 2, 2.5 and 3 (Equation 8.10).

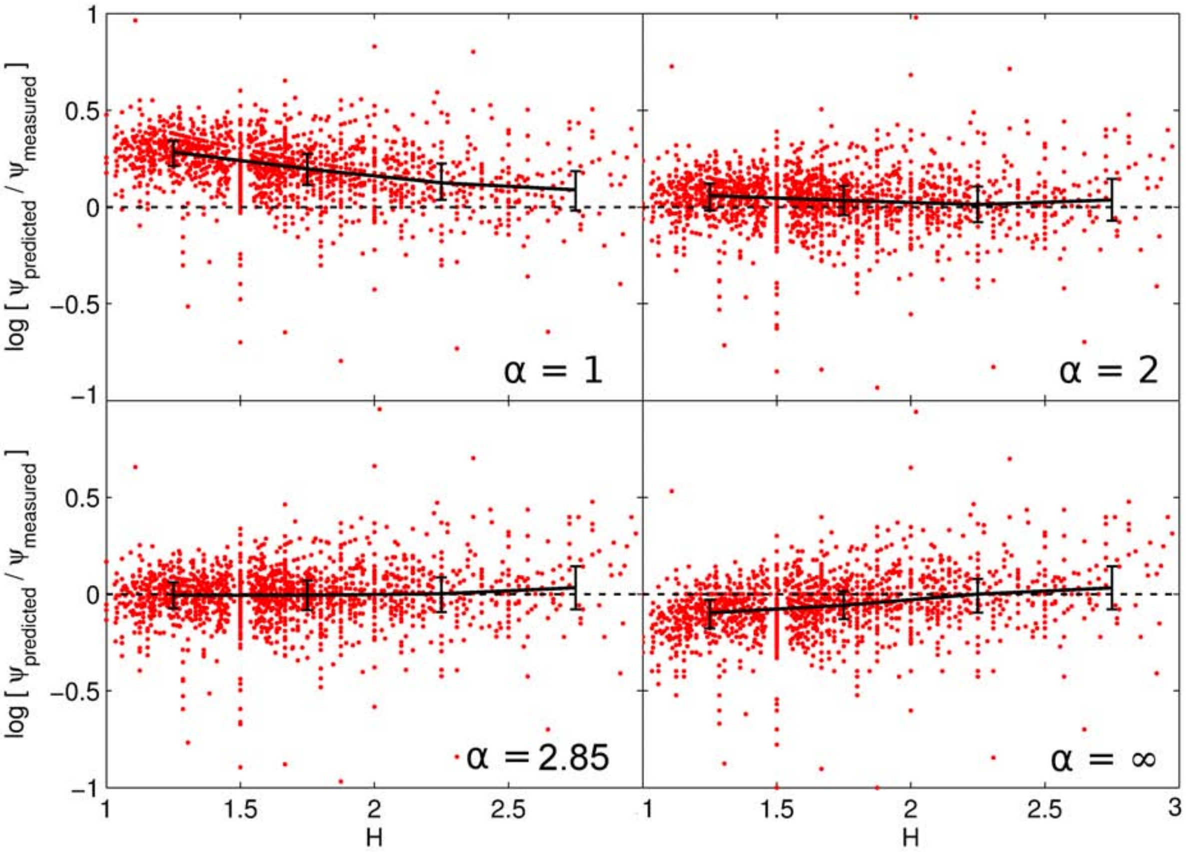


Figure 8.14: The effect of the heterogeneity $H$ (Equation 8.10) on the prediction errors of the power summation model (Equation 8.1) with several $\alpha$ values (1-Hz vibration). The lines show the median prediction error and inter-quartile ranges for 4 ranges of heterogeneity (1-1.5; 1.5-2; 2-2.5; 2.5-3).

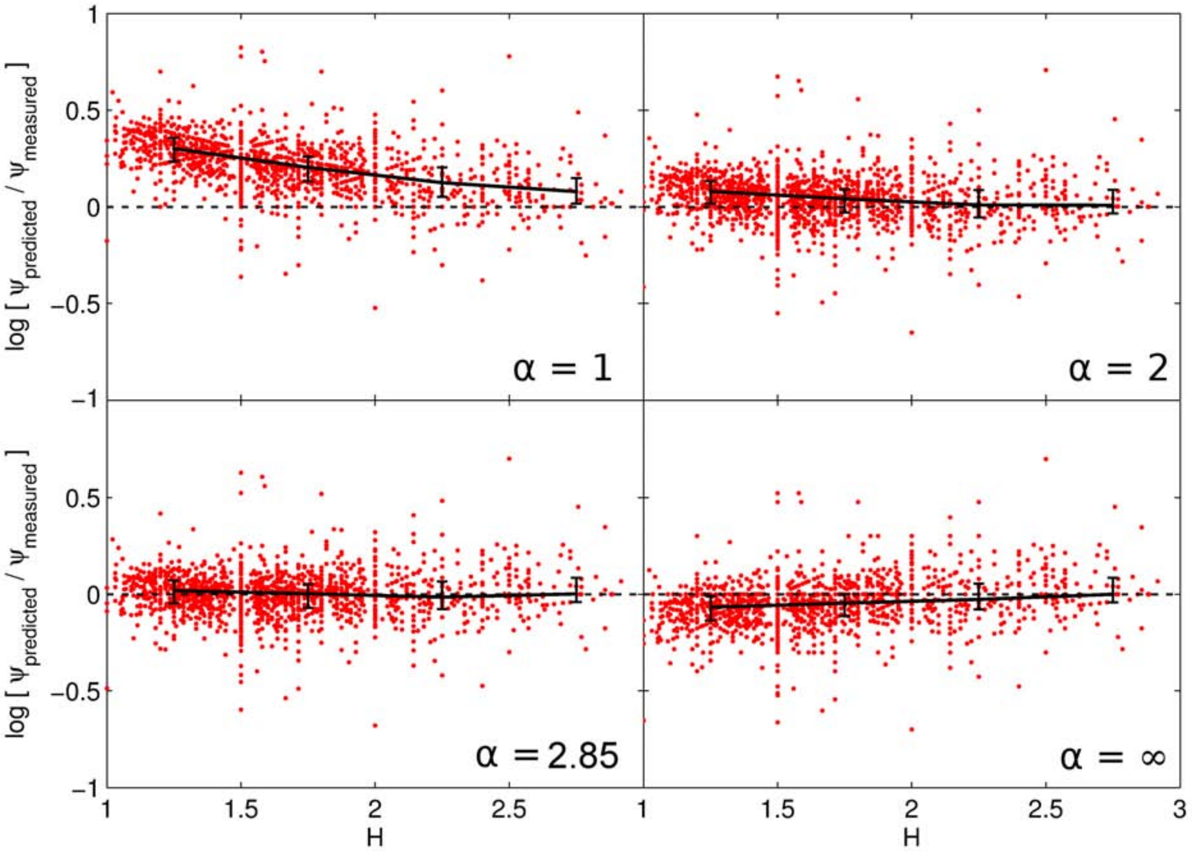


Figure 8.15: The effect of the heterogeneity $H$ (Equation 8.10) on the prediction errors of the power summation model (Equation 8.1) with several $\alpha$ values (4-Hz vibration). The lines show the median prediction error and inter-quartile ranges for 4 ranges of heterogeneity (1-1.5; 1.5-2; 2-2.5; 2.5-3).

It can be observed that the prediction error for stimuli with a low heterogeneity (i.e. motions for which the three components are similar) depends largely on the exponent. Those motions are overestimated by the linear sum and underestimated by the worst component to a greater extent than motions that have one dominant component, as would be expected.

When $\alpha = 2.85$, no effect of $H$ is visible. In Figure 8.16, the effect of $H$ on the prediction error is compared between the power summation method with $\alpha = 2.85$ and the masking method with $A = 0.19$. In both cases the median prediction errors were small for all values of $H$, although a systematic trend was observed with the masking model but not with the power summation: with the masking model, the prediction error tended to increase with $H$, and motions with $H > 2.0$ were, on average, slightly overestimated while motions with $H < 1.5$ were underestimated. No systematic trend was observed with the power summation method, and although median errors are very small in both cases, it suggests that the power summation method may be better as the value of the parameter is less dependant on the choice of test stimuli. Motions with $H > 2.5$ were slightly overestimated by both methods, but this results from a small number of test stimuli.

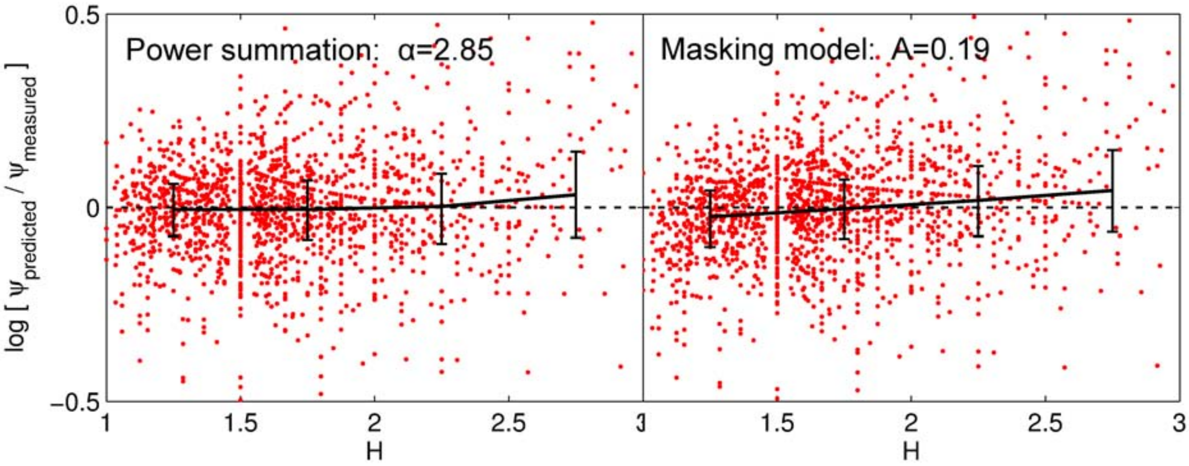


Figure 8.16: Comparison of the effect of heterogeneity on the prediction error for the power summation model and the masking model. The lines show the median prediction error and inter-quartile ranges for 4 ranges of heterogeneity (1-1.5; 1.5-2; 2-2.5; 2.5-3).

From this analysis, it can be concluded that the exponent of 2.85 found earlier is equally applicable for tri-axial motions with different relative magnitudes between components, as shown in Figure 8.16. This suggests that the summation method using an exponent of 2.85 was not the result of the particular choice of tri-axial stimuli used in the experiment, and can be applied in general situations.

### 8.4.3 The effect of stimulus magnitude

Another factor that could influence the prediction errors is the magnitude of the stimuli. Similarly to the effect of heterogeneity, the prediction methods may be the result of a particular choice of stimulus magnitudes and so this merits investigation. To investigate the interaction of stimulus magnitude with the prediction error, a measure of the magnitude has to be chosen. The prediction error was defined as:

$$error = \log\left(\frac{\psi_{predicted}}{\psi_{measured}}\right) \tag{8.11}$$

So the error was naturally positively correlated with $\psi_{predicted}$ and negatively correlated with $\psi_{measured}$. So, if $\psi_{measured}$ or $\psi_{predicted}$ were used as estimators of the magnitude of the motions, they would show an artificial correlation with the error, which is not the effect investigated. Therefore, an unbiased estimate of the subjective magnitude of the stimuli was chosen:

$$\psi_m = \frac{\psi_{measured} + \psi_{predicted}}{2} \tag{8.12}$$

The prediction error obtained with Equation (8.11) and the power summation model with $\alpha = 2.85$ is shown in Figure 8.17 as a function of the stimulus magnitude $\psi_m$. For analyzing the effect of stimulus magnitude on the prediction error, the test stimuli were grouped (arbitrarily) in six categories:

- $0 < \psi_m < 50$
- $50 < \psi_m < 100$
- $100 < \psi_m < 150$
- $150 < \psi_m < 200$
- $200 < \psi_m < 250$
- $250 < \psi_m < 300$

For each category, the median error was calculated and is shown in Figure 8.17.

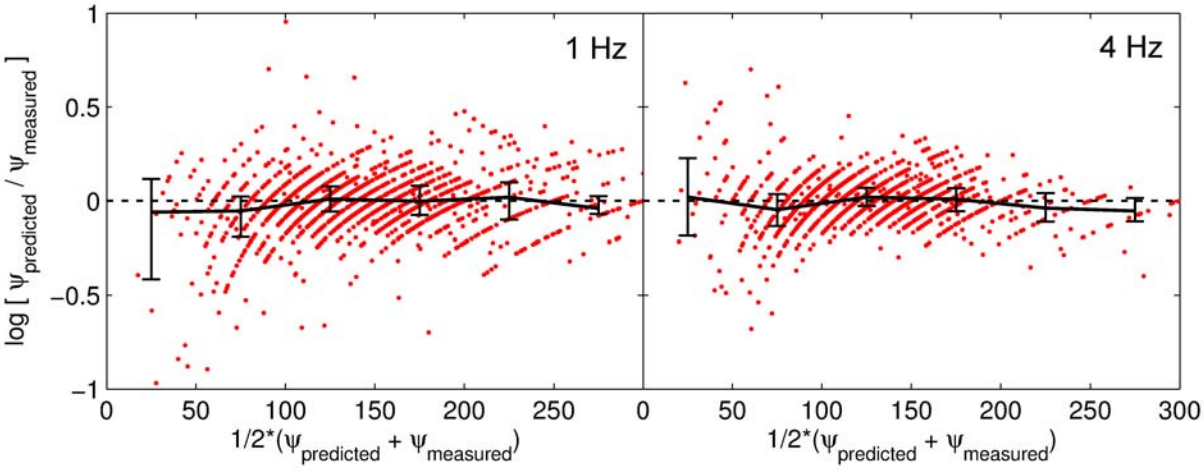


Figure 8.17: Prediction error (as indicated by Equation (8.11) obtained with the power summation model and $\alpha = 2.85$) as a function of the stimulus magnitude $\psi_m$. The lines show the median prediction error and inter-quartile ranges for 6 ranges of magnitudes (0-50; 50-100; 100-150; 150-200; 200-250; 250-300).

At both frequencies, and for all categories of stimuli, the median prediction error is close to zero. No systematic bias is observed (for example, overestimating greater magnitudes but underestimating smaller magnitudes). This suggests that the optimal prediction method determined in Section 8.3.3 was not a trade-off, and is suitable for the whole range of subjective magnitudes. This also means that the optimal value of the exponent does not result from the choice of magnitudes in the experiment.

In Figure 8.17, data points seem to be distributed on curved lines. This pattern is observed because when the method of magnitude estimation is used, subjects tend to use specific ratings, in general multiples of 10, and very rarely use ratings between these particular values. This effect is discussed in Section 9.3.4 of the general discussion. So, each line corresponds to a particular rating $\psi_{measured} = \psi_0$, and the points on the curve are all stimuli that obtained this particular rating. All stimuli that obtained that particular rating $\psi_0$ obtained different predicted discomfort, and this results in all points being located on the following parametric curve, using as parameter $t = \psi_{predicted}$:

$$\begin{cases} x(t) = \frac{1}{2}(t + \psi_0) \\ y(t) = \log\left(\frac{t}{\psi_0}\right) \end{cases} \tag{8.13}$$

which is equivalent to:

$$y = \log\left(\frac{2x}{\psi_0} - 1\right) = \log\left(\frac{2x - \psi_0}{\psi_0}\right) = \log\left(\frac{\psi_0 + 2x - 2\psi_0}{\psi_0}\right) = \log\left(1 + 2\frac{x - \psi_0}{\psi_0}\right) \tag{8.14}$$

## 8.4.4 Power summation methods in the literature

### 8.4.4.1 Standard method

In International Standard ISO 2631-1:1974 (now obsolete), it was recommended that the discomfort of multi-axis vibration is estimated as the discomfort of the most severe single-axis component, after the components had been frequency-weighted. This corresponds to the method of the worst component (Equation 8.4). After it had been criticized, it was amended in 1982, and it was thereafter recommended that the discomfort of all single-axis components were combined. In the latest version of the standard, ISO 2631-1 (1997), the method of the root-sum-of-squares of the weighted accelerations is recommended when evaluating vibration with respect to comfort:

$$a_v = \left({k_x}^2{a_x}^2 + {k_y}^2{a_y}^2 + {k_z}^2{a_z}^2\right)^{1/2} \tag{8.15}$$

where:

- $a_{wx}$, $a_{wy}$ and $a_{wz}$ are the frequency-weighted r.m.s. accelerations in the fore-and-aft, vertical and horizontal directions respectively
- $k_x$, $k_y$ and $k_z$ are multiplying factors that depend on the frequency weightings used. The values of $k$ are all equal to 1.0 in the standard evaluation method for vibration discomfort (not for health), due to an appropriate choice of frequency weightings.

This method is consistent with the findings of previous studies of the discomfort of dual-axis vibration.

#### 8.4.4.2 Previous studies

Griffin and Whitham (1977) investigated methods for predicting the discomfort of dual-axis vibration (lateral + vertical 3.15-Hz sinusoidal vibration) from the discomfort of its single-axis components. The discomfort of the multi-axis and single-axis test stimuli was measured by their equivalent magnitude (i.e. the magnitude of a single axis motion (either vertical or lateral) that causes an equivalent discomfort). This means that the discomfort of the multi-axis stimuli was predicted from the acceleration (physical magnitude) of the single-axis components, and not their discomfort (subjective magnitude).

The methods of linear sum, root-sum-of-squares, and a masking model similar to the one presented in Section 8.2.6.5 were compared. It was concluded that the linear sum overestimated the discomfort of dual-axis vibration. The masking model, once optimized, fitted the data slightly better than the root-sum-of-squares, which was an expected result of the optimization of the masking parameters. However the root-sum-of-squares provided very satisfying results, and being more suited to practical use, was finally recommended. Mistrot *et al.* (1990) used a similar method to investigate the discomfort caused by dual-axis ($x+z$ and $y+z$) 3.15-Hz and 6.3-Hz sinusoidal vibration. When trying to predict the equivalent magnitudes of dual-axis motions from the equivalent magnitudes of its components with a power-summation method, the predictions were significantly different from the results with exponents equal to 1, 3, 4, 5 or $\infty$; with an exponent of 2, no significant difference was found.

Griefahn and Bröde (1999) also took a similar approach and found that an exponent equal to 1 or 2 was better than 3, suggesting that the most appropriate value is between 1 and 2.

Fairley and Griffin (1988) took a slightly different approach and tried to determine a method for predicting the discomfort of dual-axis ($x+z$) vibration from the discomfort (subjective magnitude) of its component, and not from the accelerations (physical magnitudes). It was assumed a power summation method could be used to predict the discomfort, similarly to Equation (8.2). The optimal exponent was found to be around 2, with no large difference when the vibration frequency varied from 2.5 Hz to 10 Hz. The linear sum method was found to overestimate, and the worst component to underestimate, dual-axis discomfort. Ratios between subjective magnitudes in the two axes varied from 1:9 to 9:1, similarly to the present experiment where the acceleration ratios between components vary from 1:8 to 8:1. However, contrary to the present experiment where the discomfort of all single-axis components were obtained by magnitude estimation, in the study by Fairley and Griffin (1988), the discomfort of single-axis components was estimated with the assumption that the discomfort is linearly related to the vibration magnitude.

It has been shown in Chapter 4 that the discomfort of sinusoidal vibration varies as a function of the acceleration magnitude according to a power law:

$$\psi = k\varphi^n \tag{8.16}$$

where the exponent $n$ was found to be around 0.7 for most frequencies and directions. This means that the assumption of a linear relation between discomfort and acceleration is not justified, and the exponent of 2 found by previous studies applies to the prediction of discomfort from the weighted accelerations (physical magnitude) rather than the discomfort (subjective magnitudes) of single-axis components. This might lead to a different exponent, because of the power law relationship between the subjective and the physical magnitude (Equation 8.16)

Let us assume that vibration stimuli are compared with equivalent vibration in the (for example) lateral direction at 4 Hz, and they are measured by their equivalent magnitude (i.e. the magnitude of 4-Hz lateral vibration that causes equivalent discomfort). Then, if the fore-and-aft component has an equivalent magnitude $a_{x,eq}$ then by definition its discomfort $\psi_x$ is equal to the discomfort caused by a 4-Hz lateral vibration with magnitude $a_{x,eq}$, which is equal to:

$$\psi_x = k_y {a_{x,eq}}^{n_y} \tag{8.17}$$

where $k_y$ and $n_y$ are respectively the ‘constant’ and the ‘exponent’ in Stevens’ power law for 4-Hz lateral vibration. Similarly:

$$\psi_z = k_y {a_{z,eq}}^{n_y} \tag{8.18}$$

$$\psi_{total} = k_y {a_{total,eq}}^{n_y} \tag{8.19}$$

where $\psi_{total}$ and $a_{total,eq}$ are respectively the subjective magnitude of the tri-axial motion and its equivalent magnitude. Therefore, if $a_{total,eq}$ is estimated with the power summation of the equivalent magnitudes in all three directions using an exponent $\beta$:

$$a_{total,eq} = \left({a_{x,eq}}^{\beta} + {a_y}^{\beta} + {a_{z,eq}}^{\beta}\right)^{\frac{1}{\beta}} \tag{8.20}$$

Then:

$$k_y {a_{total,eq}}^{n_y} = k_y \left({a_{x,eq}}^{\beta} + {a_y}^{\beta} + {a_{z,eq}}^{\beta}\right)^{\frac{n_y}{\beta}} \tag{8.21}$$

$$k_y {a_{total,eq}}^{n_y} = \left[ \left( {k_y}^{\frac{1}{n_y}} a_{x,eq} \right)^{\beta} + \left( {k_y}^{\frac{1}{n_y}} a_y \right)^{\beta} + \left( {k_y}^{\frac{1}{n_y}} a_{z,eq} \right)^{\beta} \right]^{\frac{n_y}{\beta}} \tag{8.22}$$

$$k_y {a_{total,eq}}^{n_y} = \left[ (k_y {a_{x,eq}}^{n_y})^{\frac{\beta}{n_y}} + (k_y {a_y}^{n_y})^{\frac{\beta}{n_y}} + (k_y {a_{z,eq}}^{n_y})^{\frac{\beta}{n_y}} \right]^{\frac{n_y}{\beta}} \tag{8.23}$$

$$\psi_{total} = \left[ (\psi_x)^{\frac{\beta}{n_y}} + (\psi_y)^{\frac{\beta}{n_y}} + (\psi_z)^{\frac{\beta}{n_y}} \right]^{\frac{n_y}{\beta}} \tag{8.24}$$

This shows that using an exponent $\beta$ in the power summation of equivalent magnitudes is equivalent to using an exponent $\alpha$ in the power summation of discomfort such that:

$$\alpha = \frac{\beta}{n} \tag{8.25}$$

where $n$ is the growth rate of sensation (i.e., the exponent in Equation 8.16) for the reference vibration.

#### 8.4.4.3 Comparison of present results with previous studies

In the study by Griffin and Whitham (1977) cited in the previous section, the adjustable stimulus was a 3.15-Hz vertical or lateral vibration. In the study by Mistrot (1990), it was a 3.15-Hz or 6.3-Hz fore-and-aft or lateral vibration. In those conditions, the median rate of growth of sensation, $n$, varies from 0.48 to 0.91 for the adjustable vibration (Chapter 4, Table 4.7 and Appendix E.1, Table E.1).

This means that the exponent of $\alpha = 2.85$ (Equation 8.1) found optimal in the present study corresponds to values of $\beta$ between (according to Equation 8.25):

$$\beta_1 = 2.85 \times 0.48 = 1.4 \tag{8.26}$$

and:

$$\beta_2 = 2.85 \times 0.87 = 2.6 \tag{8.27}$$

This is therefore consistent with the value of $\beta = 2$ recommended by those studies, in which only integer values of $\beta$ were considered.

### 8.4.5 Predicting the discomfort of multi-axial vibration

The experimental results showed that the discomfort of a tri-axial vibration could be predicted with no bias when using a power summation model or a masking model:

$$\psi_{total} = \left(\psi_x^{2.85} + \psi_y^{2.85} + \psi_z^{2.85}\right)^{\frac{1}{2.85}} \tag{8.28}$$

$$\psi_{total} = \psi_1 + 0.19\,\psi_2 + 0.19^2\,\psi_3 \tag{8.29}$$

The masking model seemed to be calibrated to suit particular relative magnitudes of components, although the effect was small (Section 8.4.2). The power summation model was suitable for all relative magnitudes equally. The prediction error was also not dependent on the magnitude of the stimuli (Section 8.4.3). These results suggest that the optimized power summation model was not the result of the choice of the magnitudes and the composition of the tri-axial stimuli, and is applicable in a broader range of situations.

The estimation error obtained with $\alpha = 3.0$ appears to be similar to the error obtained with $\alpha = 2.85$ (Figure 8.18), so the more practical value of 3.0 might be used:

$$\psi_{total} = \left(\psi_x^{3} + \psi_y^{3} + \psi_z^{3}\right)^{\frac{1}{3}} \tag{8.30}$$

## 8.5 Conclusion

For predicting the discomfort of standing persons exposed to tri-axial random vibration, a power summation method is more practical than a method based on a masking model. Experimental results show that the discomfort of standing people exposed to multi-axis random vibration $\psi_{total}$ can be predicted by combining the discomfort caused by each of the single-axis components $\psi_x$, $\psi_y$ and $\psi_z$ as shown in Equation (8.31):

$$\psi_{total} = \left(\psi_x^{3} + \psi_y^{3} + \psi_z^{3}\right)^{\frac{1}{3}} \tag{8.31}$$

No great difference was found between 1-Hz vibration and 4-Hz vibration, although the mechanisms of discomfort for standing people are different (see Chapter 4 and 6), which suggests that these results may apply to a wider range of frequencies. The model was shown to be equally applicable to multi-axial stimuli with different total magnitude and relative magnitudes between components.

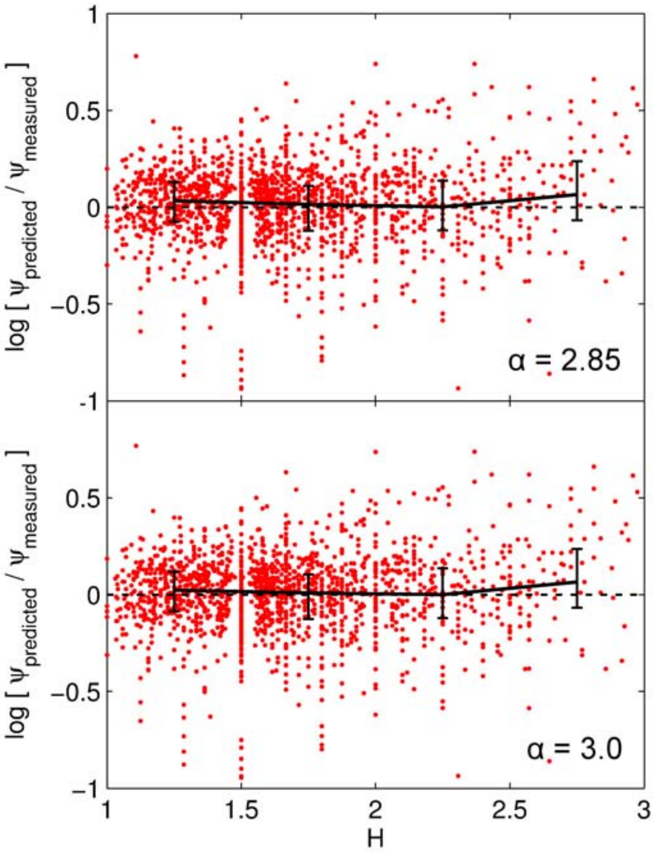


Figure 8.18: Comparison of the estimation error as a function of the heterogeneity with $\alpha = 2.85$ and $\alpha = 3.0$.

The analysis conducted in this Chapter is limited to translational vibration: the inclusion of rotational oscillation (roll, pitch, and yaw) in the model would require further experimental work.

# Chapter 9

# Discussion

## 9.1 Introduction

In this chapter, results from the experiments reported in Chapters 4 to 8 are compared and combined to allow further discussion and help build a general model of the vibration discomfort of standing people. The methods used in the experiments are also discussed in the light of the result, in order to bring recommendations for future work.

## 9.2 Discussion of the results

### 9.2.1 Comparison of the discomfort of seated people and standing people

#### 9.2.1.1 Differences in the mechanism

Most past studies of vibration discomfort were conducted with seated subjects, and the standards were derived from such studies, including the standards applying to standing subjects. Previous studies showed that equivalent sensation contours are different for standing and seated people (Section 2.3.8).

Essential differences exist between seated and standing people and may lead to differences in the vibration discomfort:

- Standing people are less stable than seated people. Standing people are therefore more likely to lose balance when exposed to some motions. This occurs particularly at frequencies between 0.5 and 1 Hz, and to a lesser extent at frequencies up to 3 Hz (Figure 9.3 and Chapter 4).

- At higher frequencies, legs have an isolation effect: the transmission of horizontal vibration to the upper body decreases with increasing frequency and almost no vibration is transmitted at frequencies greater than about 3 Hz. This isolation effect appears in Figure 9.4, where the floor-to-head transmissibility for horizontal vibration decreases as frequency increases. In Figure 9.3, the consequences of this effect on comfort appear, as the importance of discomfort in the upper body decreases with frequency.

- Vertical vibration was not expected to cause loss of balance, since it does not cause the centre of balance to move horizontally, which is usually the cause of instability when the centre of pressure approaches the limit of the base of support (Nashner, 1997). However, subjects exposed to 0.5-Hz vertical vibration experienced a feeling of loss of balance and dizziness (Figure 7.5). This sensation corresponds to the 'other cause' shown in Figure 9.3 and is an important cause of discomfort at frequencies up to 3 Hz, although its importance decreased as frequency increased. The sensation of loss of balance is probably not experienced by sitting subjects, who feel more stable, so this suggests that the perception of low-frequency motion is different for standing people.

#### 9.2.1.2 Experimental results

The considerations in the previous section suggest that the responses of standing and seated people to horizontal vibration may be different both at low frequencies (due to postural instability) and high frequencies (due to the isolation effect). This probably explains why the frequency weightings constructed in Chapter 4 are different from the weighting recommended in the standards, $W_d$ (based on the response of seated subjects), as shown in Figure 9.1.

Vertical vibration is transmitted to the upper body of standing people (Figure 9.4), as with seated people, so the response may be similar. However, at low frequencies, the sensation of balance loss experienced by the subjects (Section 9.2.1.1) may not be experienced by seated subjects. The experimental frequency weighting for vertical vibration was similar to the weighting recommended in BS 6841 (1987), $W_b$ (based on the response of seated subjects), in the frequency range 3 to 16 Hz. In the range 0.5 to 3 Hz, which corresponds to the range where dizziness and instability were experienced the weightings are different (Figure 9.2).

### 9.2.2 Model of discomfort

#### 9.2.2.1 Comparison of low frequencies and high frequencies

The observation of experimental results suggests that the frequency range 0.5 to 16 Hz can be divided into two ranges: the low frequencies (0.5 to about 3 Hz) and the high frequencies (3 to 16 Hz). Differences can be observed between these two ranges in the frequency-dependence of sensitivity to horizontal (Figure 9.1) and vertical (Figure 9.2) vibration, the cause of discomfort (Figure 9.3), the floor-to-head transmission of vibration (Figure 9.4), the effect of postural supports (Figure 9.5), and the rate of growth of sensation (Figure 9.6). In Figures 9.1 to 9.6, the limit between the two frequency ranges is shown (in Figure 9.5, the limit was set at 2.0 Hz instead of 3.0 Hz). The properties of the two frequency ranges are summarized in Table 9.1.

Table 9.1: Comparative summary of the characteristics of the vibration discomfort of standing people at low frequency (less than 3 Hz) and high frequency (greater than 3 Hz). 'Pushing supports' refers to a back support with fore-and-aft vibration or a shoulder support with lateral vibration.

| | | Low frequency | High frequency |
|---|---|---|---|
| Horizontal vibration | Frequency weighting (Figure 9.1) | Constant velocity | Constant acceleration |
| | Cause of discomfort (Figure 9.3) | Loss of balance | Discomfort in the legs |
| | Transmissibility (Figure 9.4) | High, decreasing as frequency increases | Constant, close to 0 |
| | Effect of 'pushing' supports (Figure 9.5) | Marginally improved comfort | Increased discomfort (by a factor of 2 to 3) |
| | Growth rate of sensation (Figure 9.6) | Constant, about 0.7 | Constant, about 0.7 |
| | Exponent for the evaluation (Table 7.5) | 3.0 (at 1 Hz) | 3.5 (at 8 Hz) |
| Vertical vibration | Frequency weighting (Figure 9.2) | Different from $W_b$ | Similar to $W_b$ |
| | Cause of discomfort (Figure 9.3) | Balance/dizziness | Discomfort in the lower and upper body |
| | Transmissibility (Figure 9.4) | Close to 1 | Close to 1 |
| | Growth rate of sensation (Figure 9.6) | Decreasing from 1.5 to 0.7 | Constant, about 0.7 |
| | Exponent for the evaluation (Table 7.5) | 3.0 (at 1 Hz) | 3.5 (at 8 Hz) |

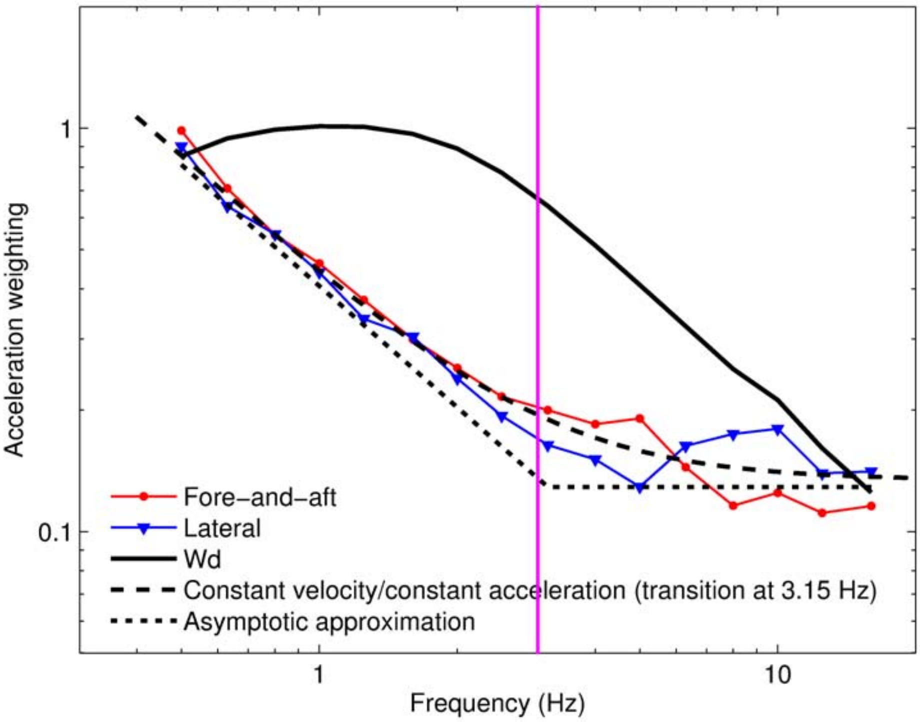


Figure 9.1: Frequency weightings constructed in Chapter 4 for horizontal vibration, compared with the weighting advocated in standards, $W_d$, and an analogue filter used to model the weightings.

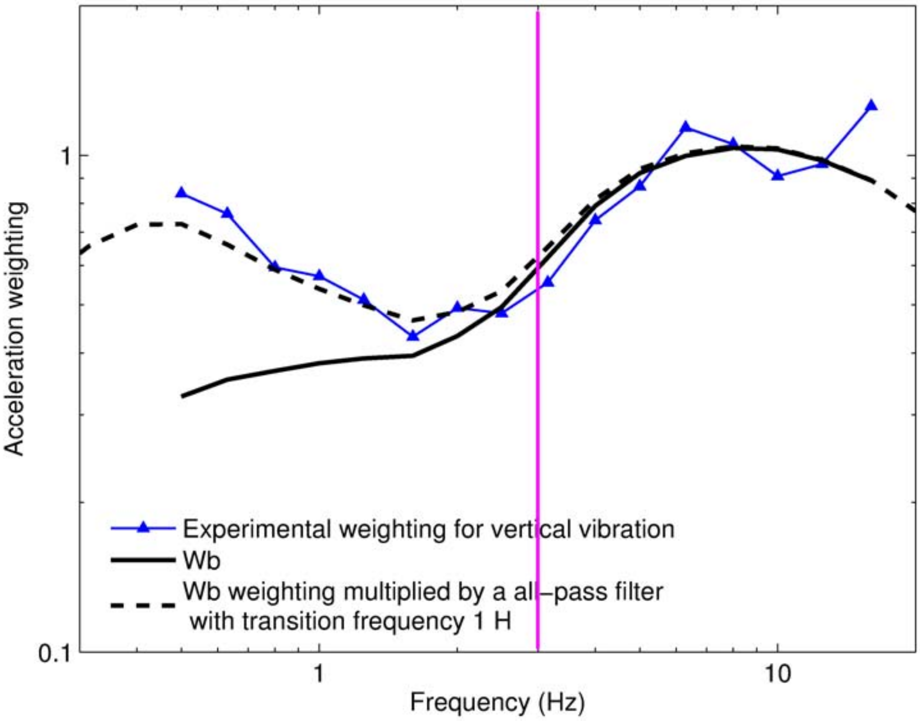


Figure 9.2: Frequency weightings constructed in Chapter 4 for vertical vibration, compared with the weighting advocated in standards, $W_b$, and an analogue filter used to model the weightings.

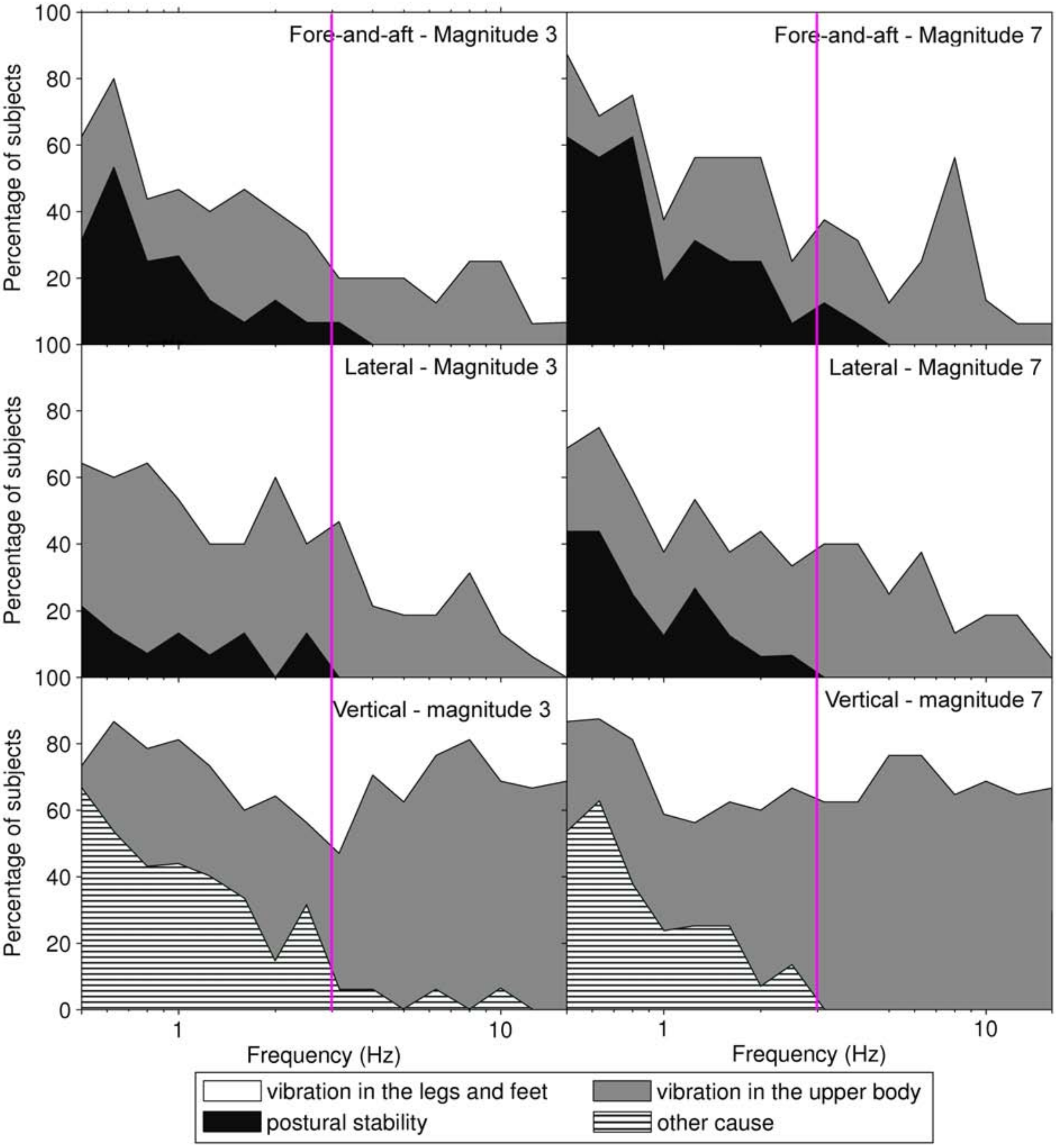


Figure 9.3: Cause of discomfort for two magnitudes of fore-and-aft, lateral, and vertical sinusoidal vibration in the range 0.5 to 16 Hz. At each frequency, the percentage of subjects reporting each factor as the main cause of discomfort is shown. These data were obtained in Chapter 4.

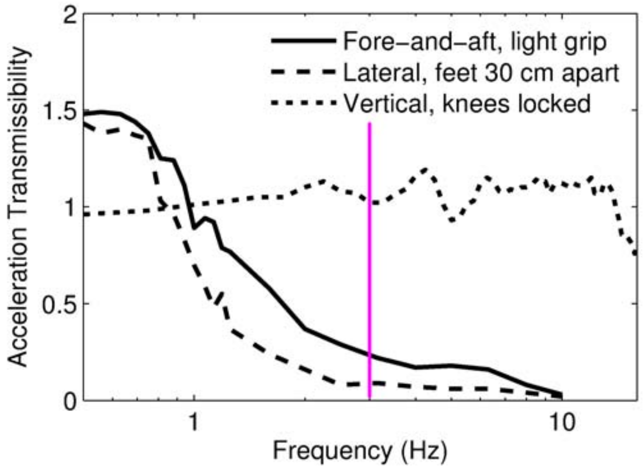


Figure 9.4: Floor-to-head transmissibility of standing people measured by Paddan and Griffin (1993b).

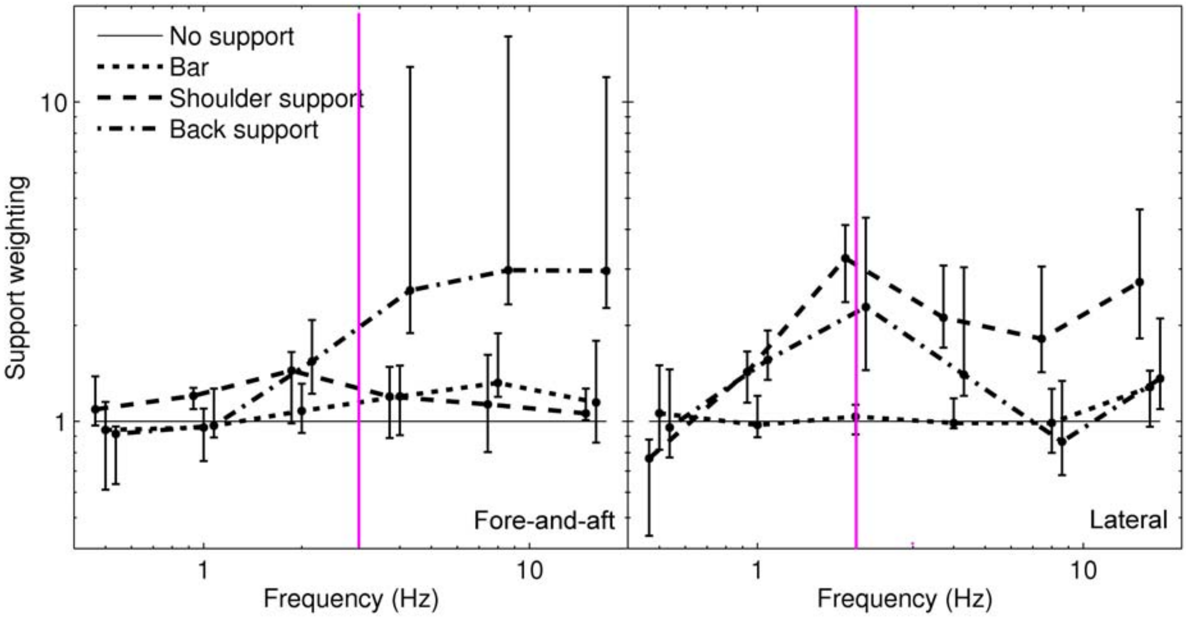


Figure 9.5: Support weightings representing the effect of postural supports in the frequency range 0.5 to 16 Hz obtained in Chapter 6. A weighting greater than 1.0 indicates that the discomfort is increased by the support.

#### 9.2.2.2 Summary of the mechanisms of discomfort of standing people

Relations can be hypothesized between the properties of the vibration discomfort in the two frequency ranges summarized in Table 9.1 and shown in Figures 9.1 to 9.6. In particular, the relation between floor-to-head transmissibility and discomfort in the upper body, and the effect of supports, has been discussed in Chapters 4 and 6. Based on the comparisons in Table 9.1, a model of the mechanisms of discomfort of standing people exposed to horizontal (Figure 9.7) and vertical (Figure 9.8) vibration was constructed. The model shows how vibration results in discomfort in each of the frequency ranges, and how postural supports affect the discomfort. For example, it shows that horizontal vibration is not naturally

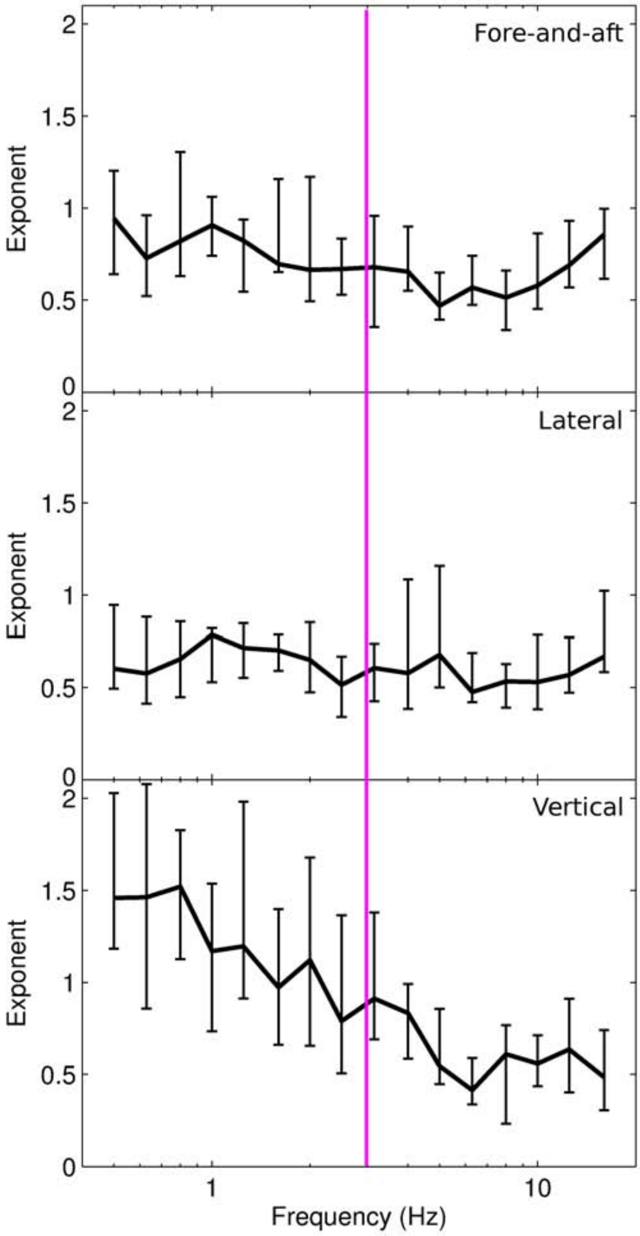


Figure 9.6: Rate of growth of sensation in Stevens' power law (Equation 3.2), obtained for fore-and-aft, lateral and vertical vibration in the range 0.5 to 16 Hz in Chapter 4.

transmitted to the upper body at high frequencies; therefore, using a support that transmits vibration to the upper body increases discomfort, whereas no such effect is observed at low frequency.

The exponent for the evaluation of vibration, $\lambda$, was different at 1 Hz and 8 Hz. This might be related with the different mechanisms, but was assumed to be related with the different length of shocks at both frequencies, because the exponent was independent of the direction despite different mechanisms being involved in different directions.

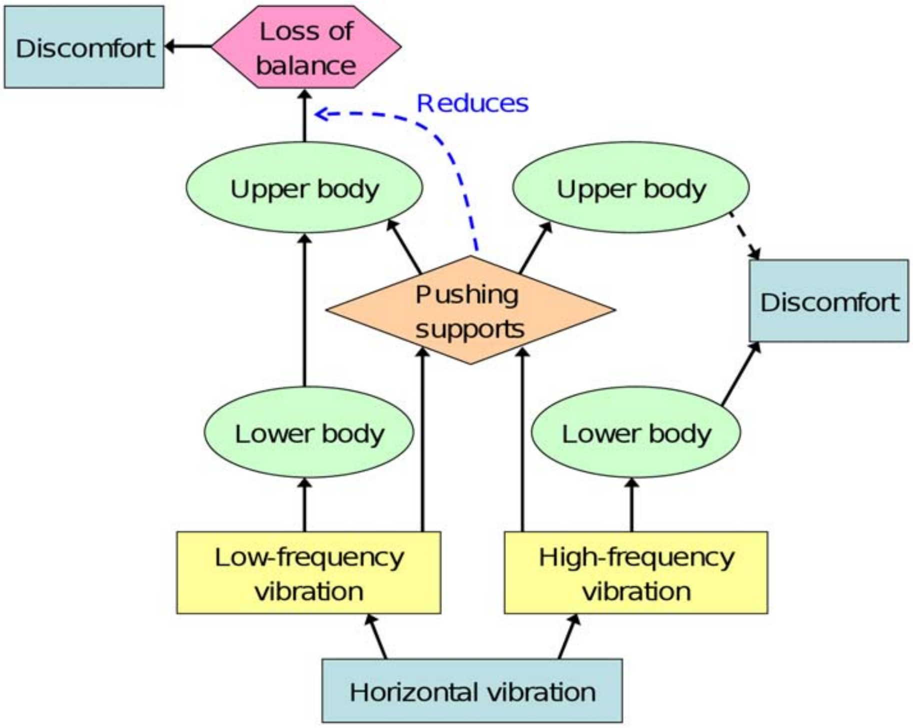


Figure 9.7: Model of the vibration discomfort for standing people exposed to horizontal vibration. ‘Lower body’ refers to the feet and legs, and ‘upper body’ refers to the rest of the body; ‘pushing supports’ refer to a back support with fore-and-aft vibration or a shoulder support for lateral vibration.

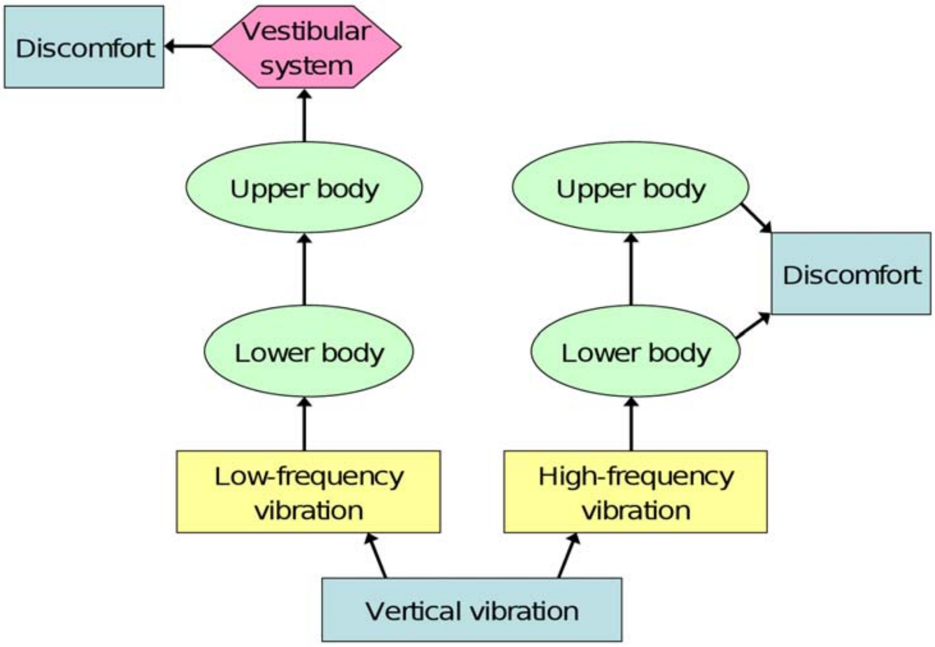


Figure 9.8: Model of the vibration discomfort for standing people exposed to vertical vibration. ‘Lower body’ refers to the feet and legs, and ‘upper body’ refers to the rest of the body. The effects of supports were not investigated.

### 9.2.3 The effect of magnitude

#### 9.2.3.1 The relation with the frequency-dependence of the exponent, $n$

In Chapters 4 and 5, frequency weightings were constructed for fore-and-aft, lateral and vertical direction that show the effect of frequency on sensitivity to acceleration. Using the same frequency weighting to evaluate vibration at all magnitudes means that it is assumed that the shape of the weighting does not depend on the magnitude of vibration. This is the case when the rate of growth of sensation n in Stevens' power law does not depend on the frequency. Stevens' power law is used to relate the subjective magnitude (i.e., the discomfort) of a vibration, $\psi$, to its physical magnitude (generally, the r.m.s. acceleration), $\varphi$:

$$\psi = k\varphi^n \tag{9.1}$$

To prove the relation between the magnitude-dependence of the weightings and the frequency-dependence of the exponent $n$, let us assume that two frequencies $f_1$ and $f_2$ are compared. At each of those two frequencies, Stevens' power law can be written:

$$\psi_1 = k_1\varphi^{n_1} \tag{9.2}$$

$$\psi_2 = k_2\varphi^{n_2} \tag{9.3}$$

If the frequency weighting was derived from an equivalent sensation contour corresponding to the subjective magnitude $\psi_0$, then the accelerations on the contour at frequencies $f_1$ and $f_2$, $a_1$ and $a_2$, are such that a vibration at frequency $f_1$ and magnitude $a_1$, and a vibration at frequency $f_2$ at magnitude $a_2$, both cause equivalent discomfort $\psi_0$:

$$k_1{a_1}^{n_1} = \psi_0 \tag{9.4}$$

$$k_2{a_2}^{n_2} = \psi_0 \tag{9.5}$$

So:

$$a_1 = \left(\frac{\psi_0}{k_1}\right)^{\frac{1}{n_1}} \tag{9.6}$$

$$a_2 = \left(\frac{\psi_0}{k_2}\right)^{\frac{1}{n_2}} \tag{9.7}$$

Since the weighting was derived by inverting the equivalent sensation contour, the ratio of the weighting value at frequency $f_1$ to the weighting value at frequency $f_2$ (the relative sensitivity) is the inverse of the ratio of the accelerations:

$$\frac{W(f_1)}{W(f_2)} = \frac{a_2}{a_1} \tag{9.8}$$

so:

$$\frac{W(f_1)}{W(f_2)} = \frac{\left(\frac{\psi_0}{k_2}\right)^{\frac{1}{n_2}}}{\left(\frac{\psi_0}{k_1}\right)^{\frac{1}{n_1}}} \tag{9.9}$$

$$\frac{W(f_1)}{W(f_2)} = \psi_0^{\frac{1}{n_2}-\frac{1}{n_1}} \frac{k_1^{\frac{1}{n_1}}}{k_2^{\frac{1}{n_2}}} \tag{9.10}$$

It appears in Equation (9.10) that the relative sensitivity between $f_1$ and $f_2$, which defines the shape of the contour when $f_2$ varies over the whole frequency range, depends on the subjective magnitude $\psi_0$ if $n_1 \neq n_2$.

#### 9.2.3.2 Experimental results

The rates of growth $n$ were calculated in Chapter 4 in the frequency range 0.5 to 16 Hz for fore-and-aft, lateral, and vertical vibration. The results are reproduced in Figure 9.6.

For fore-and-aft and lateral vibration, the growth of rate was approximately constant with frequency. Although the exponent in the fore-and-aft direction was found to depend on frequency, the differences appear to be comparable with the inter-subject variability shown by the inter-quartile ranges in Figure 9.6. For vertical vibration, the exponent was independent of frequency over the range 5.0 to 16 Hz ($p > 0.05$, Friedman). Over the range 0.5 to 5.0 Hz, multiple comparisons show that the exponent tends to decrease, as can be seen in Figure 9.6.

Therefore, the exponent can be assumed to be independent of frequency for fore-and-aft vibration and lateral vibration, and for vertical vibration in the range 5.0 to 16 Hz

At all frequencies, the exponent was not significantly different for fore-and-aft and lateral direction ($p > 0.05$, Wilcoxon). At all frequences in the range 5.0 to 16 Hz, the exponent for vertical vibration was not different from the exponents for fore-and-aft or lateral vibration.

So, except for vertical vibration in the range 0.5 to 5.0 Hz, the exponent $n$ can be considered constant at all frequencies and in all directions. For fore-and-aft and lateral vibration, and for vertical vibration in the range 5.0 to 16 Hz, the median value of the exponent can be used as a practical value of the exponent:

$$n = 0.66 \tag{9.11}$$

For vertical vibration, therefore, the magnitude-dependence of the frequency weighting cannot be ignored. If a single frequency weighting is used at all magnitudes, it will not represent appropriately the frequency-dependence of the sensitivity at low frequencies if the magnitude is too different from the magnitude used to derive the weighting in use.

#### 9.2.3.3 Quantification of the error

The error resulting from using the same frequency weighting at all magnitudes for vertical vibration can be estimated. In Equation (9.10), it was shown that the ratio of the weighting between two frequencies $f_1$ and $f_2$ (i.e. the relative sensitivity) is equal to:

$$\frac{W(f_1)}{W(f_2)} = \psi_0^{\frac{1}{n_2}-\frac{1}{n_2}} \frac{k_1^{\frac{1}{n_1}}}{k_2^{\frac{1}{n_2}}} \tag{9.12}$$

where:

- $\psi_0$ is the subjective magnitude corresponding to the equivalent sensation contour from which the weighting was derived.
- $k_1$ and $k_2$ are the constants at frequencies $f_1$ and $f_2$.
- $n_1$ and $n_2$ are the growths of rate at frequencies $f_1$ and $f_2$.

In Chapter 4, the weighting for vertical vibration was obtained with $\psi_0$=150 (with a 2.5-Hz reference vibration with magnitude 0.56 m.s$^{-2}$ r.m.s.). If $f_1$ = 0.5 Hz and $f_2$ = 16 Hz, then the median exponents are $n_1$ = 1.5 and $n_2$ = 0.6 (Table 4.5), and the weighting corresponding to a magnitude estimate of 150, $W_{150}$, is such that:

$$\frac{W_{150}(0.5\text{Hz})}{W_{150}(16\text{Hz})} = 150^{\frac{1}{0.6}-\frac{1}{1.5}} \frac{k_1^{\frac{1}{1.5}}}{k_2^{\frac{1}{0.6}}} \tag{9.13}$$

If a weighting had been constructed at a subjective magnitude of 15 (magnitude ratio of 10), then the relative sensitivity would be:

$$\frac{W_{15}(0.5\text{Hz})}{W_{15}(16\text{Hz})} = 15^{\frac{1}{0.6}-\frac{1}{1.5}} \frac{k_1^{\frac{1}{1.5}}}{k_2^{\frac{1}{0.6}}} \tag{9.14}$$

So, using Equations (9.13) and (9.14):

$$\frac{W_{15}(0.5\text{Hz})}{W_{15}(16\text{Hz})} = \left(\frac{15}{150}\right)^{\frac{1}{0.6}-\frac{1}{1.5}} \frac{W_{150}(0.5\text{Hz})}{W_{150}(16\text{Hz})} \tag{9.15}$$

$$\frac{W_{15}(0.5\text{Hz})}{W_{15}(16\text{Hz})} = 0.1\frac{W_{150}(0.5\text{Hz})}{W_{150}(16\text{Hz})} \tag{9.16}$$

This means that if the weighting value is kept the same at 16 Hz, the weighting at 0.5 Hz should be divided by about 10 when the (subjective) magnitude is divided by 10. Therefore, using the same frequency weighting at all magnitudes may result in overestimating the discomfort caused by the low frequencies by a factor of about 10 if the subjective magnitude is a tenth of the magnitude used in the experiment for constructing the median acceleration weighting curve.

#### 9.2.3.4 Working hypothesis

Despite the strong magnitude-dependence, it will be assumed in a first approach that $n_z$ does not depend on the frequency, and is constant over the whole range 0.5 to 16 Hz to the median value calculated at frequencies greater than 5 Hz and in other directions:

$$n_z = 0.66 \tag{9.17}$$

Under this hypothesis, the weighting constructed in Chapter 4 can be used at all magnitudes. However, it implies that a correction is applied for vertical vibration at frequencies less than 5.0 Hz.

## 9.3 Discussion of the methods

In all experiments, the method of magnitude estimation was used (although a different method was used in the first phase of the experiment reported in Chapter 7; see Section 7.4.1). In this section, the quality and validity of the method is discussed, in the light of the results gathered in the experiments.

### 9.3.1 Order effect

#### 9.3.1.1 Psychophysical biases

As discussed in Section 2.2.5.3 of the literature review, psychophysical methods commonly used to investigate vibration discomfort may induce biases in the response of the subjects.

For example, when methods of adjustment (also called magnitude production) are used, subjects tend to under-adjust the magnitude of the test stimulus (Fairley and Griffin, 1988), possibly to sub-consciously limit their exposure to vibration. When the method of constant stimuli is used, a bias towards judging the second motion in a pair the more uncomfortable was observed (Griffin and Whitham, 1980), although the bias could be reduced by repeating the pair of vibrations, thus presenting the stimuli in the order: reference-test-reference-test. Generally, when two vibrations are compared, the second motion tends to be perceived as more uncomfortable than the first motion.

Such bias may also happen with the method of magnitude estimation, and was taken into account in the design of the experiment reported in Chapter 5, where the analysis method was designed to cancel out a possible bias. The analysis of data in Chapter 5 can also provide an estimation of the bias in the method.

#### 9.3.1.2 Derivation of bias coefficients

In Chapter 5, equivalence coefficients were calculated which represent the relative sensitivity to vibration in a given direction compared to another direction (they were at a later stage consolidated because of the order effect investigated in the present section). For example, after it had been determined that vibration in the $y$-axis with magnitude $\varphi_{y,eq}$ was equivalent (i.e., caused equivalent discomfort) to a reference vibration in the $x$-axis with magnitude $\varphi_{x,ref}$, the equivalence coefficient for the $x$-$y$ pair was:

$$K_1(x,y) = \frac{\varphi_{x,ref}}{\varphi_{y,eq}} \tag{9.18}$$

If the ratings obtained with the method of magnitude estimation were not biased, the equivalence coefficient obtained for the $x$-$y$ group would be the inverse of the equivalence coefficient obtained for the $y$-$x$ group:

$$K_1(x,y)K_1(y,x) = 1 \tag{9.19}$$

However, it is generally assumed that subjects can underestimate or overestimate the discomfort of the test motion compared to the reference motions (for example, if the test motions are overestimated, their discomfort will be rated as more than ‘100’ even when the true discomfort of the test motion is equivalent to that of the reference motion). It is assumed that the magnitude estimate provided by a given subject is biased by a constant coefficient $\epsilon$ from the true value:

$$\psi = \epsilon\psi_0 = \epsilon k \varphi^n \tag{9.20}$$

where:

- $\psi$ is the magnitude estimate provided by the subject
- $\psi_0$ is the true value of the discomfort
- $\epsilon$ is a coefficient that can be less than 1.0 (if the test stimuli were underestimated) or greater than 1.0 (if the test stimuli were overestimated). The value of $\epsilon$ is assumed to depend on the subject and on the direction of the test stimulus, but not on the direction of the reference stimulus.

In order to determine the value of the coefficient $\epsilon$, let us assume that the reference vibration is a fore-and-aft vibration with magnitude $\varphi_{x,ref}$ and the test vibration is in the lateral direction. When the equivalence is reached, the subject provides an estimate of '100'. Let $\varphi_{y,eq}$ be the magnitude of lateral vibration at the equivalence. Then, using Equation (9.20):

$$\psi = \epsilon_y k_y {\varphi_{y,eq}}^{n_y} = 100 \tag{9.21}$$

Therefore:

$$\varphi_{y,eq} = \left(\frac{100}{k_y}\right)^{\frac{1}{n_y}} {\epsilon_y}^{-\frac{1}{n_y}} \tag{9.22}$$

Beside, let $\varphi_{y_0,eq}$ be the magnitude of lateral vibration for which the 'true equivalence' is reached (i.e. when the true value of discomfort is 100, although the reported answer may be different due to the order effect). $\varphi_{y_0,eq}$ is called the true equivalence magnitude and is such that:

$$\psi_0 = k_y {\varphi_{y_0,eq}}^{n_y} = 100 \tag{9.23}$$

So:

$$\varphi_{y_0,eq} = \left(\frac{100}{k_y}\right)^{\frac{1}{n_y}} \tag{9.24}$$

It derives from Equations (9.22) and (9.24) that:

$$\varphi_{y,eq} = \varphi_{y_0,eq} {\epsilon_y}^{-\frac{1}{n_y}} \tag{9.25}$$

Equation (9.25) means that the equivalence magnitude is different from the true equivalence magnitude if the bias coefficient $\epsilon_y$ is different from 1.0. As can be predicted, if $\epsilon_y < 1$ (subjects underestimate discomfort), the equivalence magnitude found in the experiment is greater than the true equivalence magnitude because ${\epsilon_y}^{-1/n_y}$ is greater than 1.

Now, let us assume that the reference is a lateral vibration with magnitude $\varphi_{y,ref}$ equal, for convenience, to the true equivalence magnitude found in the previous paragraph $\varphi_{y0,eq}$ (a different magnitude would provide similar results):

$$\varphi_{y,ref} = \varphi_{y0,eq} \tag{9.26}$$

Let $\varphi_{x,eq}$ and $\varphi_{x0,eq}$ be respectively the equivalence magnitude and the true equivalence magnitude of fore-and-aft vibration.

Similarly to Equation (9.25), it can be shown that:

$$\varphi_{x,eq} = \varphi_{x0,eq} {\epsilon_x}^{-\frac{1}{n_x}} \tag{9.27}$$

Also, we know that a fore-and-aft vibration with magnitude $\varphi_{x,ref}$ causes the same true discomfort as a lateral vibration with magnitude $\varphi_{y0,eq}$, by definition of $\varphi_{y0,eq}$. Therefore, by reciprocity, since the reference magnitude in the present paragraph is equal to $\varphi_{y,ref} = \varphi_{y0,eq}$, the true equivalence magnitude in the fore-and-aft direction will be equal to $\varphi_{x,ref}$:

$$\varphi_{x0,eq} = \varphi_{x,ref} \tag{9.28}$$

The equivalence coefficients $K_1$ were defined in Equation (9.18) as the ratio of the reference magnitude (in the reference direction) by the equivalence magnitude (in the test direction). Therefore:

$$K_1(x,y) = \frac{\varphi_{x,ref}}{\varphi_{y,eq}} \tag{9.29}$$

$$K_1(y,x) = \frac{\varphi_{y,ref}}{\varphi_{x,eq}} \tag{9.30}$$

Using Equation (9.25), Equation (9.29) becomes:

$$K_1(x,y) = \frac{\varphi_{x,ref}}{\varphi_{y0,eq} {\epsilon_y}^{-\frac{1}{n_y}}} \tag{9.31}$$

Similarly, using Equation (9.27), Equation (9.30) becomes:

$$K_1(y,x) = \frac{\varphi_{y,ref}}{\varphi_{x0,eq} {\epsilon_x}^{-\frac{1}{n_x}}} \tag{9.32}$$

and, using Equations (9.26) and (9.28) to replace the accelerations in Equation (9.32):

$$K_1(y,x) = \frac{\varphi_{y0,eq}}{\varphi_{x,ref}\epsilon_x{}^{-\frac{1}{nx}}} \tag{9.33}$$

Therefore, using Equations (9.31) and (9.33):

$$K_1(x,y)K_1(y,x) = \frac{\varphi_{x,ref}}{\varphi_{y_o,eq}\epsilon_y{}^{-\frac{1}{ny}}}\frac{\varphi_{y0,eq}}{\varphi_{x,ref}\epsilon_x{}^{-\frac{1}{nx}}} = \epsilon_x{}^{\frac{1}{nx}}\epsilon_y{}^{\frac{1}{ny}} \tag{9.34}$$

Similarly, it can be showed that:

$$K_1(x,z)K_1(z,x) = \epsilon_x{}^{\frac{1}{nx}}\epsilon_z{}^{\frac{1}{nz}} \tag{9.35}$$

$$K_1(y,z)K_1(z,y) = \epsilon_y{}^{\frac{1}{ny}}\epsilon_z{}^{\frac{1}{nz}} \tag{9.36}$$

From Equations (9.34), (9.35) and (9.36) the expression of the bias can be derived:

$$\epsilon_x = \left[\frac{K_1(x,y)K_1(y,x)K_1(x,z)K_1(z,x)}{K_1(z,y)K_1(y,z)}\right]^{\frac{nx}{2}} \tag{9.37}$$

$$\epsilon_y = \left[\frac{K_1(x,y)K_1(y,x)K_1(y,z)K_1(z,y)}{K_1(z,x)K_1(x,z)}\right]^{\frac{ny}{2}} \tag{9.38}$$

$$\epsilon_z = \left[\frac{K_1(x,z)K_1(z,x)K_1(y,z)K_1(z,y)}{K_1(x,y)K_1(y,x)}\right]^{\frac{nz}{2}} \tag{9.39}$$

where $n_x$, $n_y$ and $n_z$ are the rates of growth of sensation for fore-and-aft, lateral and vertical vibration respectively at the frequency of the test stimuli (4 Hz). These rates of growth were calculated in the analysis of the experiment reported in Chapter 5, to perform linear regressions.

### 9.3.1.3 Values of bias coefficients

Using Equations (9.37), (9.38), and (9.39), the bias coefficients $\epsilon$ for each subject and each direction of test stimuli investigated in Chapter 5 were calculated and are shown in Table 9.2.

It appears that some subjects tended to underestimate vibration ($\epsilon < 1$) and others tended to overestimate vibration ($\epsilon > 1$). Overall, the values of $\epsilon$ were not significantly different

Table 9.2: Estimates of the magnitude estimation bias $\epsilon$ for each subject and each direction of test vibration, as calculated with Equations (9.37), (9.38) and (9.39).

| | Fore-and-aft | Lateral | Vertical |
|---|---|---|---|
| Subject 1 | 1.15 | 1.01 | 1.13 |
| Subject 2 | 0.82 | 0.92 | 1.00 |
| Subject 3 | 0.49 | 0.96 | 1.02 |
| Subject 4 | 0.97 | 0.96 | 1.04 |
| Subject 5 | 0.87 | 0.85 | 0.88 |
| Subject 6 | 1.09 | 0.96 | 0.89 |
| Subject 7 | 0.95 | 0.98 | 0.98 |
| Subject 8 | 0.72 | 0.73 | 0.76 |
| Subject 9 | 1.37 | 1.18 | 1.29 |
| Subject 10 | 0.71 | 1.08 | 1.11 |
| Subject 11 | 1.00 | 0.96 | 1.12 |
| Subject 12 | 0.97 | 0.93 | 0.94 |
| Median | 0.96 | 0.96 | 1.01 |

from 1.0, in the fore-and-aft, lateral, or vertical direction, or if the three directions were pooled together ($p > 0.18$, Wilcoxon). This means that in each direction, the effect of subjects overestimating the discomfort was counterbalanced by subjects underestimating the discomfort, and the order effect should not affect significantly the outcome of the experiment when median results are considered.

## 9.3.2 Repeatability

### 9.3.2.1 Variability

In the experiment reported in Chapter 5, sixty test stimuli were presented, in random order, in pairs with reference stimuli. The 60 test stimuli were presented again in the same session, in a different random order. This allows investigation of the repeatability of the method of magnitude estimation, by comparing the ratings obtained at the first and second presentation of an identical pair of stimuli, and the presence of a systematic effect, in particular the second rating being significantly less or more than the first rating.

For each subject and each test motion, the following ratio was calculated:

$$r = \frac{\psi_1}{\psi_2} \tag{9.40}$$

where $\psi_1$ and $\psi_2$ are the magnitude estimates reported by the subject at, respectively, the first and second presentation of the test stimulus.

The distribution of the $r$ ratio is shown in Figures 9.9 (in linear scale) and 9.10 (logarithmic scale), and the characteristics of that distribution are shown in Table 9.3.

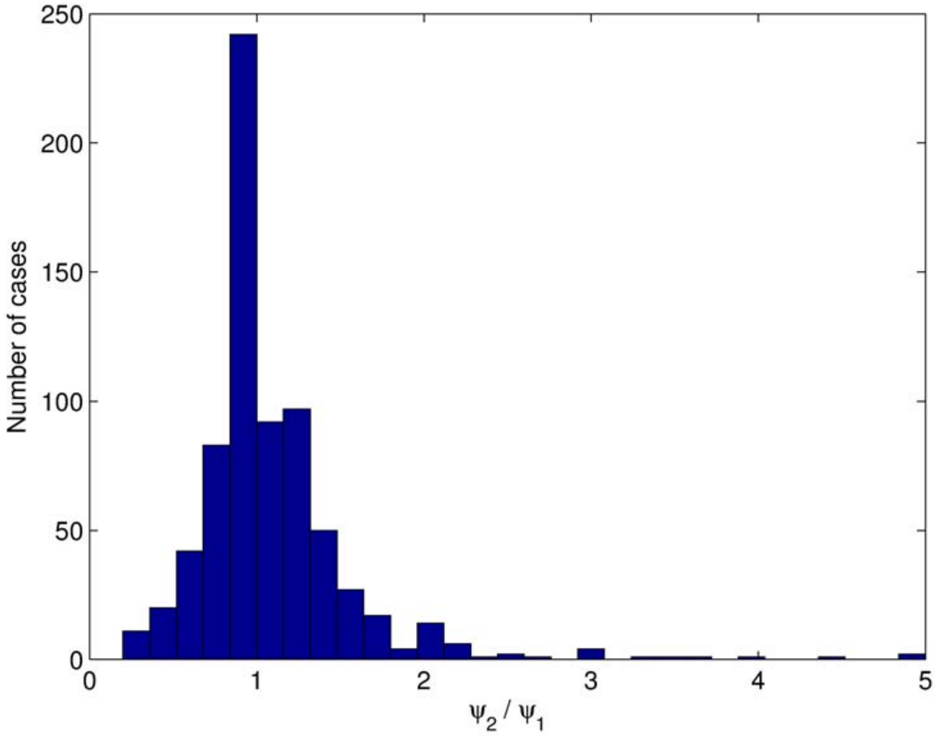


Figure 9.9: Distribution of the repeatability ratio $r = \psi_2/\psi_1$.

It was hypothesized that the first and second answers of the subjects, $\psi_1$ and $\psi_2$, were independent random variables distributed according to log-normal distributions with mean $\psi_0$, where $\psi_0$ is the 'true' estimate (Hartmann, 1997, Chapter 16; in particular, this implies that the probability density is maximum at $\psi_0$, and that it is equal at $\psi_1 = \psi_0/2$ and at $\psi_1 = 2\psi_0$). Therefore, for a given subject exposed to a given test stimulus presented twice (with a true subjective magnitude $\psi_0$):

$$\log(\psi_1) \sim \mathcal{N}(\psi_0, \sigma_1) \tag{9.41}$$

$$\log(\psi_2) \sim \mathcal{N}(\psi_0, \sigma_1) \tag{9.42}$$

where $\mathcal{N}(\mu, \sigma)$ represents the normal distribution with mean $\mu$ and standard deviation $\sigma$, and $\sigma_1$ is the standard deviation of the distribution.

The difference of two independent and identically distributed normal variables of standard deviation $\sigma$ is a normal variable with mean 0 and a standard deviation $\sqrt{2}\sigma$ (Hartmann, 1997, Chapter 16). Therefore:

$$\log(r) = \log(\psi_1) - \log(\psi_2) \sim \mathcal{N}\left(0, \sqrt{2}\sigma_1\right) \tag{9.43}$$

The true rating $\psi_0$ was different for all ratings, but it was hypothesized that the standard deviation which represent the variability in the magnitude estimates, $\sigma_1$, was constant. This implies that all values of $\log(r)$ can be pooled together, and are distributed normally with mean 0 and standard deviation $\sigma_2 = \sqrt{2}\sigma_1$.

A normal distribution with mean 0 was fitted to the distribution of $\log(r)$. As shown in Figure 9.10, the distribution can be modelled with a normal distribution of mean 0 and standard deviation $\sigma_2$=0.12. Therefore, using Equation (9.43):

$$\sqrt{2}\sigma_1 = \sigma_2 = 0.12 \tag{9.44}$$

$$\Rightarrow \sigma_1 = \frac{0.12}{\sqrt{2}} = 0.08 \tag{9.45}$$

This means that when the true discomfort for a stimulus was $\psi_0$, the estimates provided by subjects were distributed log-normally, with mean $\psi_0$ and standard deviation 0.08:

$$\log(\psi) \sim \mathcal{N}\left(log(\psi_0), 0.08\right) \tag{9.46}$$

This distribution is shown in Figure 9.11.

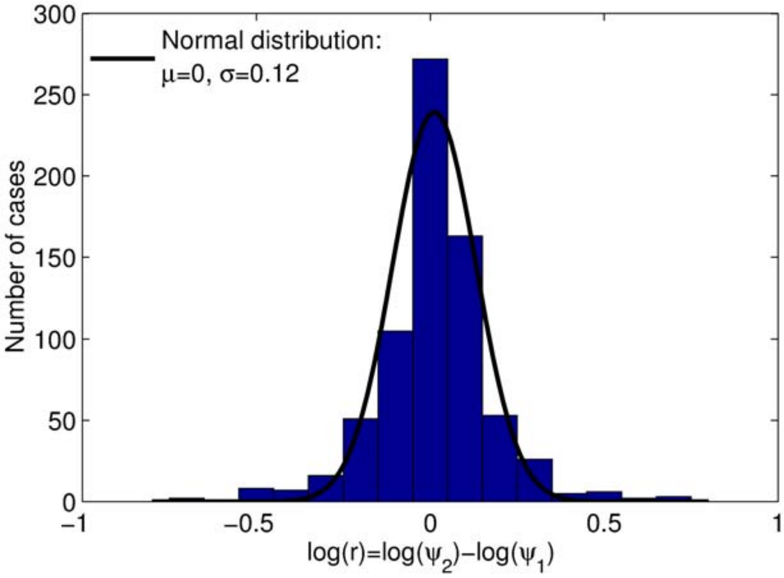


Figure 9.10: Distribution of the repeatability ratio $\log(r) = \log(\psi_2/\psi_1)$, and fitted normal distribution.

Table 9.3: Characteristics of the distribution of the $r$ ratio (Figure 9.9).

| | |
|---|---|
| 25th percentile | 0.88 |
| Median value | 1 |
| 75th percentile | 1.21 |
| Cases where $\psi_1 < \psi_2 (r < 1)$ | 322 (45%) |
| Cases where $\psi_1 = \psi_2 (r = 1)$ | 143 (20%) |
| Cases where $\psi_1 > \psi_2 (r > 1)$ | 255 (35%) |

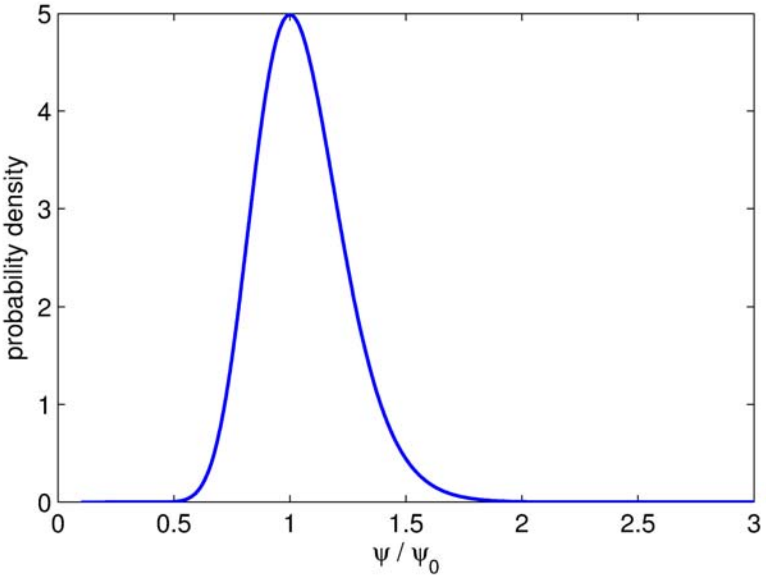


Figure 9.11: Log-normal model of the distribution of magnitude estimates $\psi$ compared to the 'true' rating $\psi_0$: $\log\left(\frac{\psi}{\psi_0}\right) \sim \mathcal{N}(0, 0.08)$.

Given the distribution shown in Figure 9.11, for a stimulus of true discomfort '100', the probability that the estimate provided by a subject is between 91 and 110 (less than 10% error) is:

$$p_{10\%} = 0.40 \tag{9.47}$$

The probability that the rating is between 67 and 150 (less than 50% error) is:

$$p_{50\%} = 0.97 \tag{9.48}$$

So, when the true discomfort is $\psi_0$, the rating is almost always between $0.67\psi_0$ and $1.5\psi_0$.

In the experiment reported in Chapter 5, each stimulus was presented twice and the geometric mean of the two ratings was used in the analysis:

$$\psi_{mean} = \sqrt{\psi_1 \psi_2} \tag{9.49}$$

$$\Rightarrow \log\left(\psi_{mean}\right) = \frac{1}{2}\left[\log(\psi_1) + \log(\psi_2)\right] \tag{9.50}$$

In the hypothesis that $\log(\psi_1)$ and $\log(\psi_2)$ are normally distributed with mean $\log(\psi_0)$ and standard deviation $\sigma_1$ (Equations (9.41) and (9.42)):

$$\log(\psi_1) + \log(\psi_2) \sim \mathcal{N}\left(2\psi_0, \sqrt{2}\sigma_1\right) \tag{9.51}$$

$$\Rightarrow \frac{1}{2}\left[\log(\psi_1) + \log(\psi_2)\right] \sim \mathcal{N}\left(\psi_0, \frac{1}{\sqrt{2}}\sigma_1\right) \tag{9.52}$$

$$\Rightarrow \log\left(\psi_{mean}\right) \sim \mathcal{N}\left(\psi_0, \frac{1}{\sqrt{2}}\sigma_1\right) \tag{9.53}$$

This means that taking the average of two ratings reduces the variability by a factor equal to $\sqrt{2}$.

#### 9.3.2.2 Bias

As shown in Table 9.3, in 20% of the cases, $r$ was exactly equal to 1.0, which means the magnitude estimate reported at the second presentation was exactly equal to the magnitude estimate at the first presentation. The number of cases in which the second estimate was greater than the first estimate (322) was greater than the number of cases where the second estimate was smaller (255) and, overall, the second estimate was significantly greater than the first estimate ($p = 0.0046$, Wilcoxon). However the difference was small.

Over the first period (including the first presentation of all stimuli), the median rating was 100 and the mean rating was 105. Over the second period of the experiment (including the second presentation of all stimuli) the median rating was also 100 and the mean rating was 108, which is 3% more than for the first period.

#### 9.3.2.3 Conclusion

To conclude, some variability was observed in the magnitude estimates; the difference between two ratings of the same stimuli (separated in time by about 30 minutes) is generally less than 20%, but it shows the necessity of performing linear regressions with a sufficient number of points, to reduce the variability by an averaging process. It can also be useful to repeat each test stimulus twice and use the average of the two magnitude estimates, as in Chapter 5, which reduces the variance by a factor of $\sqrt{2}$.

The rating obtained at the second presentation of each stimulus was significantly greater than the rating obtained at the first presentation, and the difference was about 3% on average. This may be due the magnitude estimates tending to increase over a session, and although the effect was small, it shows the necessity of randomizing the order of presentation of the test stimuli, with a different order for each subject.

### 9.3.3 Limited range of ratings

It is often assumed that when the method of magnitude estimation is used, subjects cannot provide accurate estimates if the test stimulus is excessively uncomfortable compared to the reference stimulus. The range of numbers used by subjects when using the magnitude estimation is, in practice, limited (although subjects are instructed to use any number they feel appropriate), so if the test motion is too different from the reference, an effect of saturation may occur where the subjects provide the same number for any magnitude greater than a given threshold.

In the experiment reported in Chapters 4 to 8, a total of 23,240 magnitude estimations were performed over 176 experimental sessions. The distribution of the magnitude estimates is shown in Figures 9.12 (in linear scale) and 9.13 (in logarithmic scale). The characteristics of the distribution are also reported in Table 9.4.

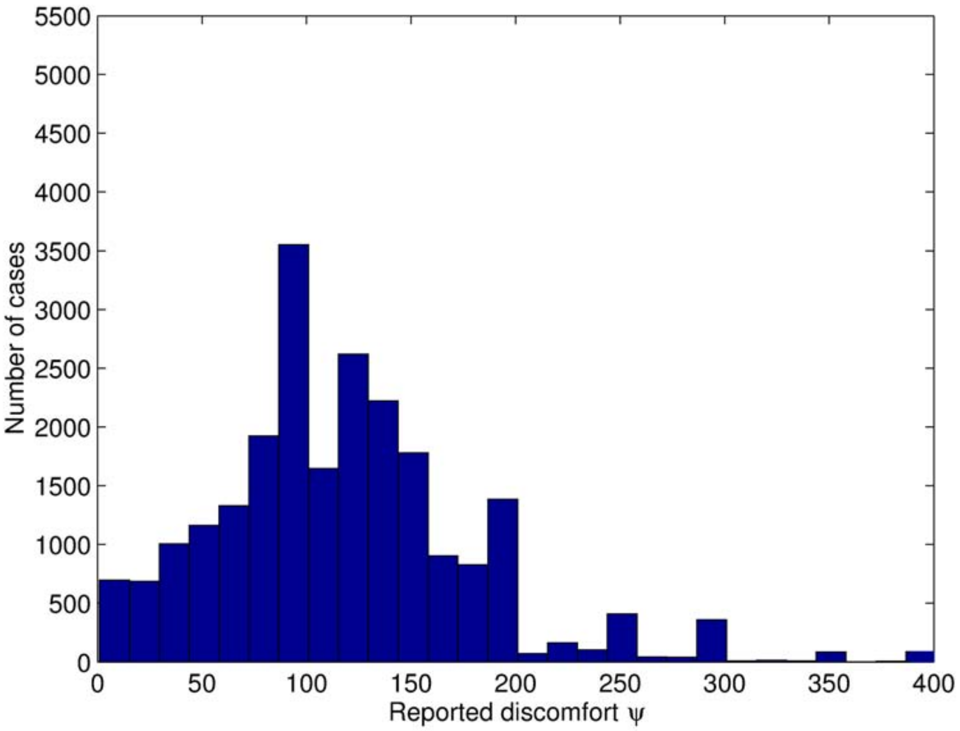


Figure 9.12: Distribution of the 23,240 magnitude estimates obtained in all experimental sessions (linear scale).

Although the full range of subjective magnitudes reported by subjects was broad (1 to 2000), the extreme values were exceptional, and 95% of the magnitude estimates were between 10 and 300 (Table 9.4). The distribution of magnitude estimates was approximately centred on 100, as shown in Figure 9.12: this is probably due to the choice of test stimuli

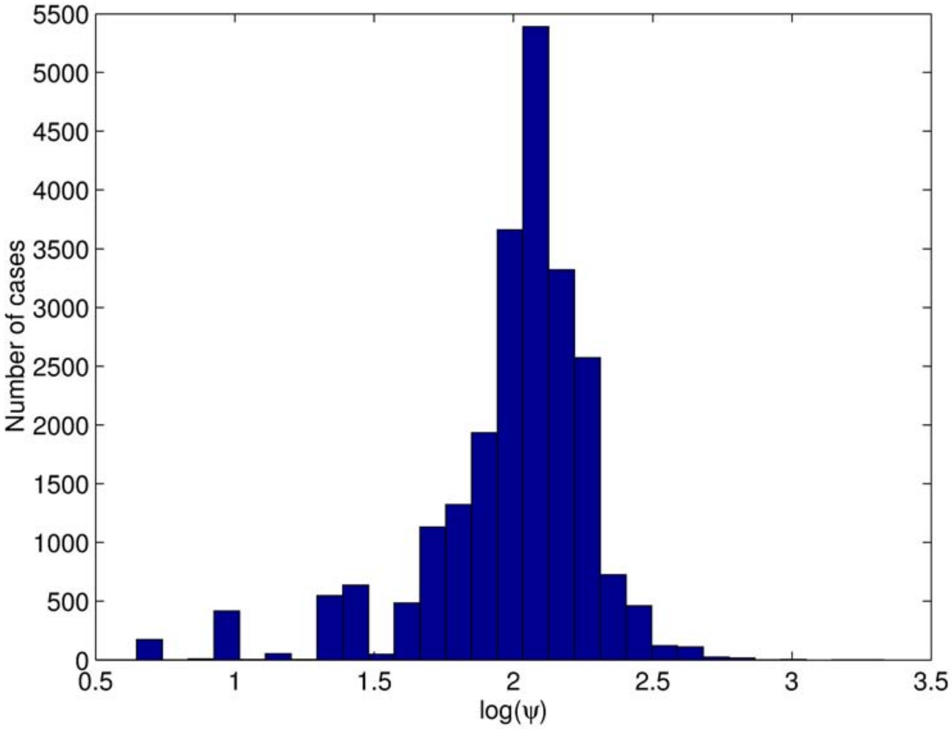


Figure 9.13: Distribution of the 23,240 magnitude estimates obtained in all experimental sessions (logarithmic scale).

Table 9.4: Characteristics of the distribution of the magnitude estimates $\psi$ (Figure 9.12.

| | |
|---|---|
| Minimum | 1 |
| 0.5th percentile | 5 |
| 2.5th percentile | 10 |
| 25th percentile | 80 |
| Median | 110 |
| 75th percentile | 150 |
| 95.5th percentile | 300 |
| 97.5th percentile | 400 |
| Maximum | 2000 |

ranges, which were centred in the magnitude of the reference stimulus. A notable feature of the distribution is the abrupt decrease in the frequency of magnitude estimates observed at a value of ‘200’ (Figure 9.12). This suggests that subjects used extensively the subjective magnitude range 0-200, but very rarely used estimates greater than 200 (6% of the magnitude estimates). The abrupt decrease suggests that this may not only be the result of the choice of magnitude, but possibly an aversion of subjects to ratings greater than 200.

If this hypothesis was verified, it would mean that the ratio of the test stimulus magnitude to the reference stimulus magnitude should be kept small enough to avoid hitting a possible ‘saturation’ effect. In the lower magnitudes, it seems that very few ratings were less than 30 ($\log(30) = 1.5$, Figure 9.13). To determine whether saturation may have happened in the experiments, the magnitude estimates of stimuli with the largest magnitude and the second largest magnitude in each set of stimuli were analyzed. The distributions are shown in Figure 9.14. It appears that the rating '200' was used more frequently than would be expected, possibly indicating a saturation effect where many stimuli for which the 'true' value was greater than '200' were rated as '200'. About 18% of the stimuli with the greatest magnitude in each set of stimuli obtained the rating 200, indicating that in any case less than 18% of them were affected by a saturation effect. About 9% of the second largest stimuli were rated '200'. These results suggest that although some saturation may have happened, it affected only the few stimuli with the largest magnitudes, and a minority of subjects.

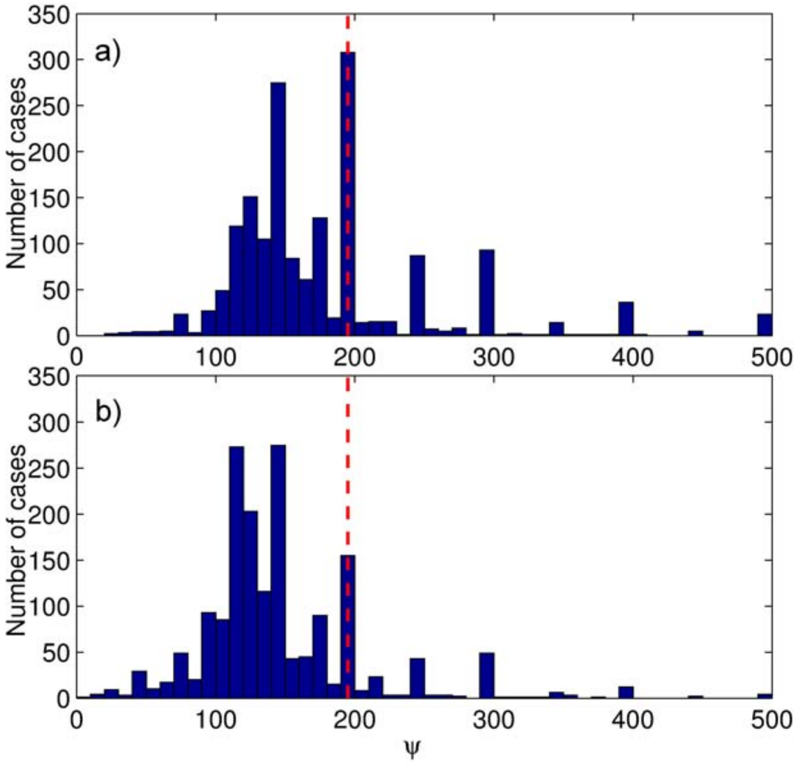


Figure 9.14: Distribution of the magnitudes estimate reported for: a) the stimulus with the greatest magnitude in each set; b) the stimulus with the second greatest magnitude in each set. The frequency of the value '200' is greater than expected.

### 9.3.4 Discrete range of ratings

When analyzing the results of the experiments, it appeared that subjects did not use any possible number for rating, but tended to use 'round' values. The number of times each integer value in the range 0 to 300 was used in the experiments is shown in Figure 9.15.

Most of the ratings used by the subjects were multiples of ten. Among the 23,240 ratings provided by all subjects in all experiments, 91% were multiples of ten and 98% were multiples of five. This is probably due to subjects not feeling that the accuracy of their rating

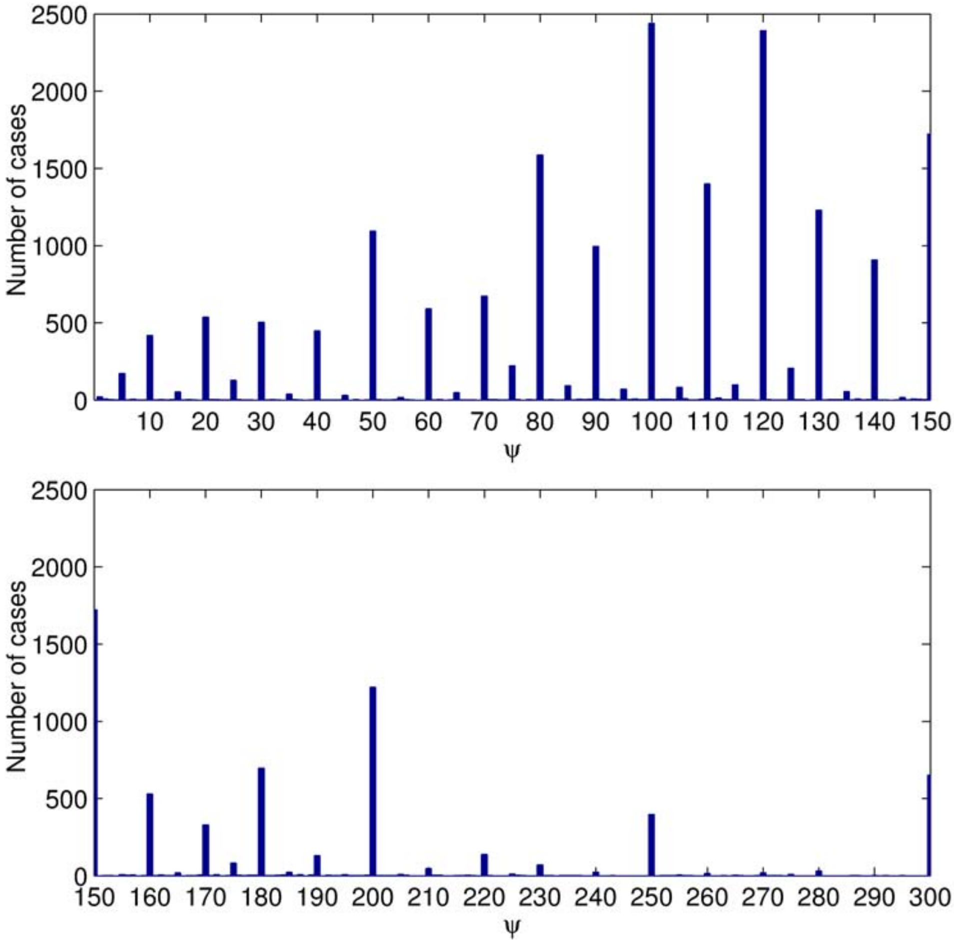


Figure 9.15: Distribution of the use of each integer number from 1 to 300 as magnitude estimates.

was greater than that corresponding to 5, or possibly 10, so using non-multiples of 5 or 10 would be unjustified; also, using round numbers is more convenient and intuitive.

This means that the estimates provided by the subjects can be considered, statistically, as rounded values, with a resolution of 10. This justifies the use of non-parametric statistics in many cases, but does not compromise the results of the experiments: generally, linear regressions were performed with at least nine points, and magnitude estimates covering a large range between, typically, 50 to 200; so any error induced by the ‘rounding’ effect should be cancelled in the regression process.

### 9.3.5 Range effects

In each experiment, the sets of stimuli in different conditions (e.g. at different frequency, in different directions, or with different supports) were chosen so as to produce a similar discomfort. For example, in Chapter 4, the range of magnitudes was designed to cause approximately equivalent discomfort at each frequency. If this choice had not been made and the same acceleration had been used at all frequencies, the same acceleration of horizontal vibration could be imperceptible at high frequencies while being dangerous at low frequencies. Also, the saturation effect investigated in Section 9.3.3 means that the range of stimuli must be controlled.

This choice may, however, affect the result. For example, if subjects tend to give a rating of '100' to a stimuli in the middle of the range of presented magnitudes at a given frequency, the equivalent comfort contour for the subjective magnitude '100' will follow the shape of the chosen magnitude ranges. Suzuki (1998a) showed that the range of magnitudes affects the outcome of an experiment if a method of magnitude estimation without reference is used, because subjects tend to use the same range of ratings regardless of the range of magnitudes presented. Several methods can be used to reduce this effect. Using a reference in the method of magnitude estimation limits this effect. Also, randomizing the test stimuli during a session (and mixing conditions together) will prevent the subject from perceiving the range of magnitudes at each frequency. As a result, the results in the experiments did not seem to be affected by the detailed choice of magnitudes: In Figure 9.16, the equivalent comfort contours obtained in Chapters 4 and 6 in similar conditions are shown, with the range of acceleration used. Although the magnitude ranges had different shapes in the two experiments (also, different subjects samples and a different reference stimulus were used), the equivalent comfort contours were not affected by this choice and are very consistent from one experiment to another.

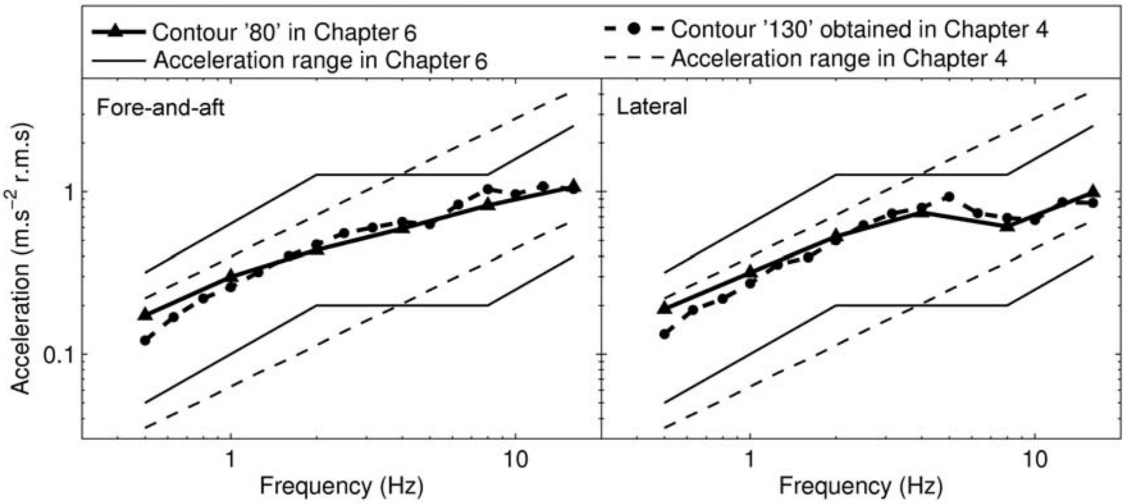


Figure 9.16: Comparison of the ranges of magnitude and equivalent comfort contours obtained in Chapters 4 and 6 (see Appendix E.6, Table E.8).

### 9.3.6 The choice of subjects

#### 9.3.6.1 Number of subjects

For each experiment, the number of subjects was chosen based on statistical power estimations. If, for example, two quantities are going to be compared in an experiment using a particular statistical test, and their distributions are known (in particular their standard deviation), and the size of the mean difference between the two quantities can be estimated, it is possible to estimate the number of subjects required to achieve a power of 0.85. The statistical power is equal to $1 - \beta$ where $\beta$ is the probability of type-II errors. This means that the power is the probability of finding a significant effect if there actually is a difference.

The power calculations were very approximate estimations, because:

- No simple method exists for calculating non-parametric statistical power (Monte-Carlo simulations are generally used). So, although the actual tests used in the experiments were non-parametric (Section 3.5.2), the power was calculated assuming the equivalent parametric tests would be used. Non-parametric tests are usually less powerful than their parametric equivalents.
- The distributions are rarely known. For the experimental design, they were generally based on the previous experiments, which provided an estimate of the dispersion of magnitude estimates.
- The effect size was rarely known. Generally, an effect size considered significant (for example, 10% difference) was fixed, and the number of subjects necessary to detect an effect of that size with power 0.85 was determined.

When the processing of the data was complex (Chapters 7 and 8), the simplest method to calculate the power was making use of Monte-Carlo simulations. A large number of random data samples were simulated, based on simple models, and the proportion of cases where a significant effect was observed was used as an estimate of the statistical power.

The number of subjects was chosen slightly larger than the values suggested by the power analysis, since non-parametric tests, which were used in the experiments, tend to be less powerful than parametric tests, which were used in the power analysis.

#### 9.3.6.2 Characteristics of subjects

In all experiments, subjects were male, aged 20-38 years, who were university students or staff. It is relevant to decide whether this particular choice of subjects limits the scope of applications for the results. As discussed in Section 2.3.7.1 of the literature review, previous studies did not find an effect of gender on the response of seated subjects to vibration. It is not expected to be different with standing subjects. The choice of male subjects was partly justified by the availability of more male subjects than female subjects. Also, as pointed out in Section 2.3.7.1, Spång (1997) suggested that the variability of response is much greater with females.

The age was not found to affect the vibration discomfort either (Section 2.3.7.2 in literature review) for seated subjects. For standing subjects, in conditions where postural stability was involved (i.e. when subjects were exposed to fore-and-aft or lateral vibration at frequencies less than about 3 Hz, see Figure 9.3), the age would probably influence the response, since the postural control system evolves with age, making older people more liable to lose balance. This means that if the model was to be applied to elderly passengers exposed to vibration, the frequency weightings might have to be adapted to give more importance to low-frequency horizontal vibration, using the results in Figure 9.3.

## 9.4 Recommendations

### 9.4.1 The method of magnitude estimation: choice of magnitudes

As discussed in Section 9.3.3, the range of ratings that subjects use with the method of magnitude estimation seems to be limited. Although the subjects are instructed to use any number that seems suitable, it seems that they rarely use numbers greater than 200. Although this may be due to the choice of magnitudes, the results seemed to suggest that ‘saturation’ may have occurred, where subjects tended to avoid using ratings greater than 200 when the ‘real’ subjective magnitude was above 200. If this was true, the experimenter using the method of magnitude estimation should limit the ranges of stimuli so that the subjective magnitude does not exceed about double the magnitude of the reference. However, further investigation is needed to determine with certainty whether this effect occurs.

### 9.4.2 Linear regression and variability

In Section 9.3.2, the magnitude estimates obtained at the first presentation of a test stimulus were compared with the magnitude estimates obtained at the second presentation of the same stimulus, in the same session. As expected, the ratings were not exactly repeatable, and some variability was observed. It was concluded that when the true rating for a test stimulus was $\psi_0$, the ratings provided by the subjects were almost always (with probability 0.97) between $0.67\psi_0$ and $1.5\psi_0$. The data used for this analysis was collected when subjects compared a test and a reference in different directions. The difference of direction probably added variability, so less variability would be expected when the reference and the test are in the same direction.

In most experiments, to cancel the effect of variability, linear regressions were performed between the subjective and objective magnitudes. The experimenter must make sure that the number of points in the linear regression is sufficient, taking the dispersion into account.

### 9.4.3 Randomization of the presentation order

In Section 9.3.2.2, it was suggested that the magnitude estimates provided by some subjects tend to increase over the duration of a session. This effect may create a bias in the experimental data. To avoid this, it is important to randomize the order of presentation of the test stimuli in a session, and to use a different random order for all subjects. This way, a bias will tend to be cancelled in the averaging processes.

### 9.4.4 The effect of age and gender

All experiments were conducted with male subjects aged 20 to 38 years. Although past studies generally found no significant effect of gender, and no effect of age on the vibration discomfort of seated people (Section 9.3.6.2), the discomfort of standing people may be affect by these variables. In particular, postural instability (which does not happen with seated subjects) is expected to depend on age. Experiments with subject samples more representative of the general populations are required.

## 9.5 Conclusion

The method of magnitude estimation allows possible biases that were analysed using the experimental results. No major bias compromising the validity of the results was found, although recommendations for future work were made.

The comparative analysis of the results from the experiments lead to a model of discomfort caused by horizontal and vertical vibration (Figures 9.7 and 9.8). The model is based on the observed difference between vibration discomfort at low frequencies (less than about 3 Hz) and high frequencies (greater than 3 Hz). In these frequency ranges, the mechanisms of discomfort are different and lead to different frequency-dependence and different effects of supports.

# Chapter 10

# Predictive model

## 10.1 Introduction

Chapters 4 to 8 investigated different aspects of the vibration discomfort of standing people so that a model can be constructed integrating the findings of all experiments. The structure of the model (similar to the structure of the work presented in Figure 1.1 in the Introduction) is shown in Figure 10.1. The purpose of the model is to be able to evaluate tri-axial vibration. This means that, for a given recorded or simulated floor vibration, the model must be able to provide a value representing the discomfort of standing people exposed to the vibration motion. This is not sufficient to assess the vibration, for example judge whether it is acceptable, very uncomfortable, etc. However, it must allow comparison between two motions, and determine which one is more uncomfortable.

Individual sensitivity varies from one person to another, so an evaluation is not representative of the perception of all people. It is rather an average of what would be observed with a sample of subjects or passengers. Indeed, most findings were derived from average values obtained with samples of subjects.

In all experiments, test stimuli were 6-seconds long. Therefore, the effect of duration was not investigated, and the model applies for the comparative evaluation of same-duration stimuli; also the model applies to short duration stimuli, such as 6 seconds.

The construction of the model is detailed in Sections 10.3 to 10.6.

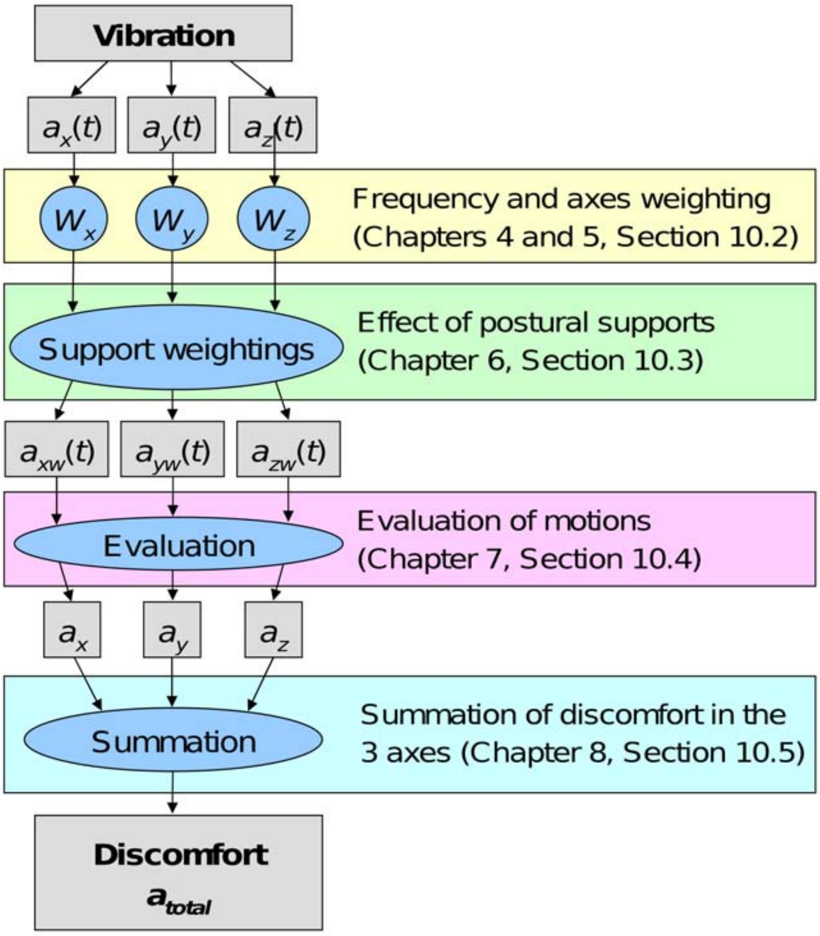


Figure 10.1: Structure of the model.

## 10.2 Limits of the model

### 10.2.1 Exclusion of rotations

The model only includes translational motions. That means that if the vibration motions also contain rotations, any additional discomfort caused by the rotational components is not included in the evaluation. Integrating rotations is a complex problem for several reasons. Rotations are very different from translations. Translational displacement and velocity do not themselves cause discomfort: what causes discomfort is the variation of velocity (i.e. the acceleration). A subject standing on a floor in translational movement with constant velocity (and in particular, with constant displacement, i.e. an immobile floor) would not experience any discomfort. However, constant rotational displacement can cause discomfort: a subject standing on a floor that is not horizontal is not fully comfortable. This is an essential difference between rotations and translations. Also, if translational acceleration is measured at the floor, rotational displacement results in gravity being included in the measurement of horizontal acceleration.

In all situations, rotations inherently interfere with translations, in their definition, their measurement, and their effect on discomfort, which is the reason why their analysis is very complex and needs extensive further investigation before being included in a model.

### 10.2.2 Statistical distributions

The experimental results on which the model is based were obtained in experiments conducted with samples of subjects assumed to be representative of the general population. Generally, parameters were median or mean values obtained from the sample, so the model represents the 'average' person, and is expected to provide average discomfort prediction. As such, it does not provide information about the distribution among a population. Such knowledge would enable more advanced predictions, for example confidence intervals. This may have been possible, but only in situations where the method used for the analysis of data was itself simple enough, in particular the construction of frequency weightings. A different experimental design would have been needed.

### 10.2.3 Assessment and evaluation

In this section, the term 'evaluation' refers to the production of a value representing the discomfort caused by a vibration stimulus, while 'assessment' refers to the production of a subjective judgement (often based on an evaluation), such as 'hardly perceptible', 'fairly uncomfortable', or 'dangerous'.

The model described in this chapter provides an evaluation of the vibration. An evaluation is a numerical value representing the discomfort of the vibration motion and making possible, in particular, the comparison of vibration stimuli. An assessment of the vibration would be a judgement of the severity of the vibration. For example, assessment of a vibration can rank the vibration motion on a severity scale including labels such as 'not perceptible', 'perceptible', 'uncomfortable', 'unbearable'.

The model does not provide an assessment of the vibration. Absolute judgements depend on a number of variables, including subject experience and the context of a vibration. A magnitude of vibration perceived as normal and acceptable in a second class train carriage may be perceived as annoying in a first class carriage, and would be unacceptable in a building. Therefore, providing an assessment is a difficult task, and an evaluation may be more useful for practical applications.

## 10.3 Frequency weighting

### 10.3.1 Horizontal vibration

In Chapter 5, frequency weightings were proposed for standing people based on experimental results. For horizontal vibration, they were constructed as follows (Figure 5.5):

- For fore-and-aft vibration, an all-pass filter asymptotically equal to constant velocity ($|H(\omega)| \propto 1/\omega$) at low frequencies and constant acceleration ($|H(\omega)| \propto 1$) at higher frequencies was used. The transition frequency was at 4 Hz.
- For lateral vibration, a filter similar to the filter used for fore-and-aft vibration was used, but with a transition frequency at 3.15 Hz.

Although the effect of vibration outside the range 0.5 to 16 Hz has not been investigated in this thesis, the weightings must be defined beyond this range.

At frequencies greater than 20 Hz, vibration has generally no effect on the discomfort of train passengers (ISO 2631-4, 2001, Section 4) so the extension of the weighting at frequencies greater than 16 Hz is not crucial. Miwa (1968c) constructed equivalent comfort contours for standing people exposed to horizontal vibration in the range 3 to 100 Hz (Figure 2.4 in the literature review). The equivalent comfort contours were similar to lines of constant velocity; although the results obtained by Miwa (1968c) at frequencies less than 16 Hz differ from the results of the present study, in the absence of other information it can be assumed that at frequencies outside the scope of the present study, the sensitivity decreases according to lines of constant velocity (as explained earlier, this choice has little importance for practical applications as vibration at frequencies greater than 20 Hz are rare in trains). Such a decrease of sensitivity can be modelled by multiplying the frequency weightings suggested in Chapter 5 by a first-order low-pass filter with a transition frequency sufficiently greater than 16 Hz to avoid modifying the weighting at frequencies less than 16 Hz. A frequency of 80 Hz was a suitable value.

Vibration at frequency 0.5 Hz does not often cause discomfort in specific body parts: the main cause of discomfort is postural instability. As a consequence, it can be assumed that at frequencies less than 0.5 Hz, the main cause of discomfort is postural instability (Figure 4.11). The results by Nawayseh and Griffin (2006) found that the balance disturbance caused by narrow-band random is approximately constant when acceleration is constant in the frequency range 0.125 to 0.5 Hz. To represent this effect, the frequency weighting should be constant at frequencies less than 0.5 Hz.

These considerations lead to the construction of a frequency weighting described by an analogue filter with the following transfer function:

$$H_1(s) = A \frac{\omega_1 s}{s^2 + \omega_1 s + {\omega_1}^2} \frac{s + \omega_2}{\omega_2} \frac{\omega_3}{s + \omega_3} \tag{10.1}$$

where:

- $s = i\omega = 2\pi i f$
- $\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$ and $\omega_3 = 2\pi f_3$ are transition frequencies.
- $A$ is a scale factor

The choice of frequencies and scale factors were different for fore-and-aft and lateral vibration. The frequency weightings for fore-and-aft and lateral vibration were represented by analogue filters with the respective transfer functions:

$$H_x(s) = A_x \frac{s + \omega_{1,x}}{s} \frac{\omega_{1,x} s}{s^2 + 2\zeta_1 \omega_{1,x} s + {\omega_{1,x}}^2} \frac{s + \omega_{2,x}}{\omega_{2,x}} \frac{\omega_{3,x}}{s + \omega_{3,x}} \tag{10.2}$$

$$H_y(s) = A_y \frac{s + \omega_{1,y}}{s} \frac{\omega_{1,y} s}{s^2 + 2\zeta_1 \omega_{1,y} s + {\omega_{1,y}}^2} \frac{s + \omega_{2,y}}{\omega_{2,y}} \frac{\omega_{3,y}}{s + \omega_{3,y}} \tag{10.3}$$

where :

- $\omega_j = 2\pi f_j, j$ =1..3
- $s = i\omega = 2\pi i f$
- $A_x = 1.9$
- $A_y = 1.5$
- $f_{1,x} = 0.5$ Hz , $f_{2,x} = 4.00$ Hz , $f_{3,x} = 80$ Hz
- $f_{1,y} = 0.5$ Hz , $f_{2,y} = 3.15$ Hz , $f_{3,y} = 80$ Hz
- $\zeta_1 = \frac{1}{2Q_1}$
- $Q_1 = 0.6$

The choice of different values for $f_2$ in the fore-and-aft and lateral directions is explained in Section 5.4.5. The gains of the transfer functions in Equations (10.2) and (10.3) are shown in Figure 10.2, with the experimental weightings determined in Chapter 4 and 5.

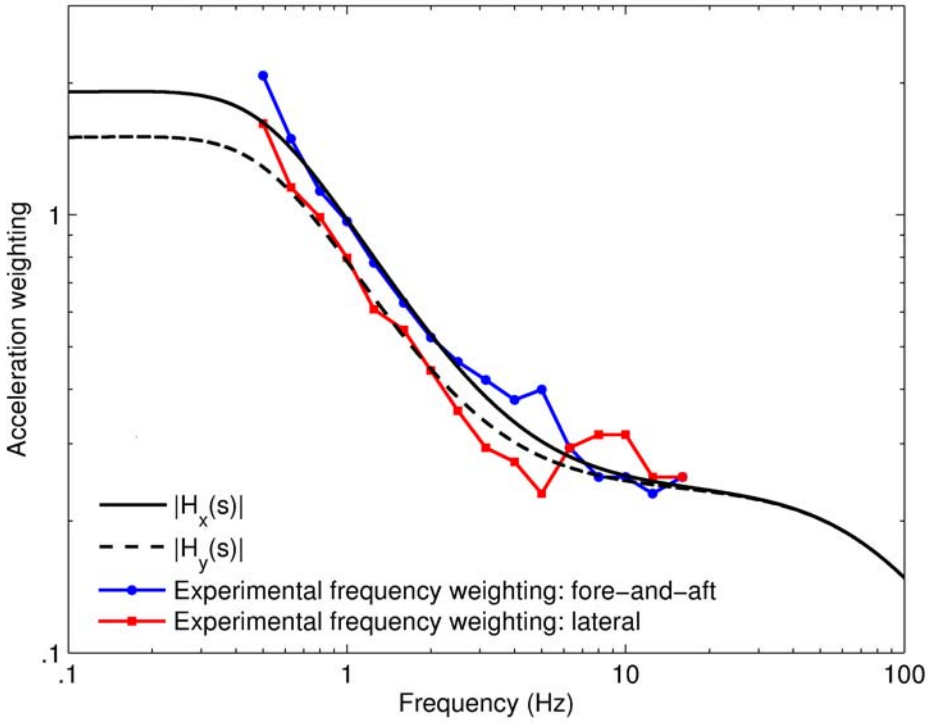


Figure 10.2: Frequency weightings defined in Equations (10.2) and (10.3) and frequency weightings determined in Chapters 4 and 5.

### 10.3.2 Vertical vibration

In Chapter 4, a frequency weighting was constructed for vertical vibration in the range 0.5 to 16 Hz (Figure 4.9). The weighting was similar to the frequency weighting recommend in standards for seated and standing people exposed to vertical vibration, $W_b$, except at frequencies less than about 2 Hz where the weighting was greater: for example, the sensitivity at 0.5 Hz was equivalent to the sensitivity at 5 Hz. To represent this effect, the frequency weighting $W_b$ was multiplied by an 'all-pass' filter corresponding to constant velocity ($|H(\omega)| \propto 1/\omega$) at frequencies less than 1 Hz, and constant acceleration ($|H(\omega)| \propto 1$) at frequencies greater than 1:

$$H_0(s) = \frac{s + \omega_0}{s} \tag{10.4}$$

where $\omega_0 = 2\pi f_0$ and $f_0 = 1$ Hz. Although the sensitivity to vertical vibration outside the frequency range 0.5 to 16 Hz was not investigated, the frequency weightings must be defined beyond this range.

Previous studies suggest that the sensitivity of standing people to vertical acceleration decreases as frequency increases beyond 16 Hz, in agreement with the frequency weighting $W_b$ advocated in standards (Figure 2.1). It can therefore be assumed that the weighting $W_b$ can be left unmodified at frequencies at frequencies greater than 16 Hz.

The sensitivity to vertical vibration at 0.5 Hz was relatively high. At this frequency, vertical vibration causes discomfort for a reason other than discomfort in a specific body part (Chapter 4, Figure 4.11). More specifically, the cause of discomfort at 1 Hz (hence probably at 0.5 Hz) appeared to be a combination of dizziness and postural instability (Chapter 7, Figure 7.5). It can be assumed that at frequencies less than 0.2 Hz, such effect will be less likely to be perceived, so the frequency weighting can decrease. This is modelled by the frequency weighting constructed as follows. The sensitivity to motion sickness is probably high from 0.125 to 0.25 Hz, as suggested by the frequency weighting $W_f$ recommended in ISO 2631-1 (1997) for the evaluation of vertical vibration in relation with motion sickness. As a consequence, the weighting constructed in this section is not expected to be suitable for predicting motion sickness.

In BS 6841 (1987) the frequency weighting $W_b$ is described by the transfer function showed in Equation (10.5):

$$H_{W_b}(s) = K\, H_{band}(s)\, \frac{s+\omega_3}{\omega_3}\, \frac{{\omega_4}^2}{s^2+2\zeta_2\omega_4 s+{\omega_4}^2}\, \frac{s^2+2\zeta_3\omega_5 s+{\omega_5}^2}{\omega_5}\, \frac{{\omega_6}^2}{s^2+2\zeta_4\omega_6 s+{\omega_6}^2} \tag{10.5}$$

where:

$$H_{band}(s) = \frac{s^2}{s^2+2\zeta_1\omega_1 s+{\omega_1}^2}\, \frac{{\omega_2}^2}{s^2+2\zeta_1\omega_2 s+{\omega_2}^2} \tag{10.6}$$

The values of the parameters are shown in Table 10.1 (with $\omega_j = 2\pi f_j, j = 1..6$)

Table 10.1: Values of the parameters for the frequency weighting $W_b$.

| | |
|---|---|
| $f_1$ | 0.4 Hz |
| $f_2$ | 100 Hz |
| $f_3$ | 16 Hz |
| $f_4$ | 16 Hz |
| $f_5$ | 2.5 Hz |
| $f_6$ | 4 Hz |
| $Q_1$ | 0.71 |
| $Q_2$ | 0.55 |
| $Q_3$ | 0.9 |
| $Q_4$ | 0.95 |
| $K$ | 0.4 |

The frequency weighting proposed for vertical vibration was obtained by multiplying this frequency weighting by the filter described by the transfer function in Equation (10.4):

$$H_z(s) = H_{Wb}\, \frac{s+\omega_0}{s} \tag{10.7}$$

where $\omega_0 = 2\pi f_0$ and $f_0 = 1$ Hz. The experimental frequency weighting, the weighting $W_b$ and $|H_z|$ are shown in Figure 10.3.

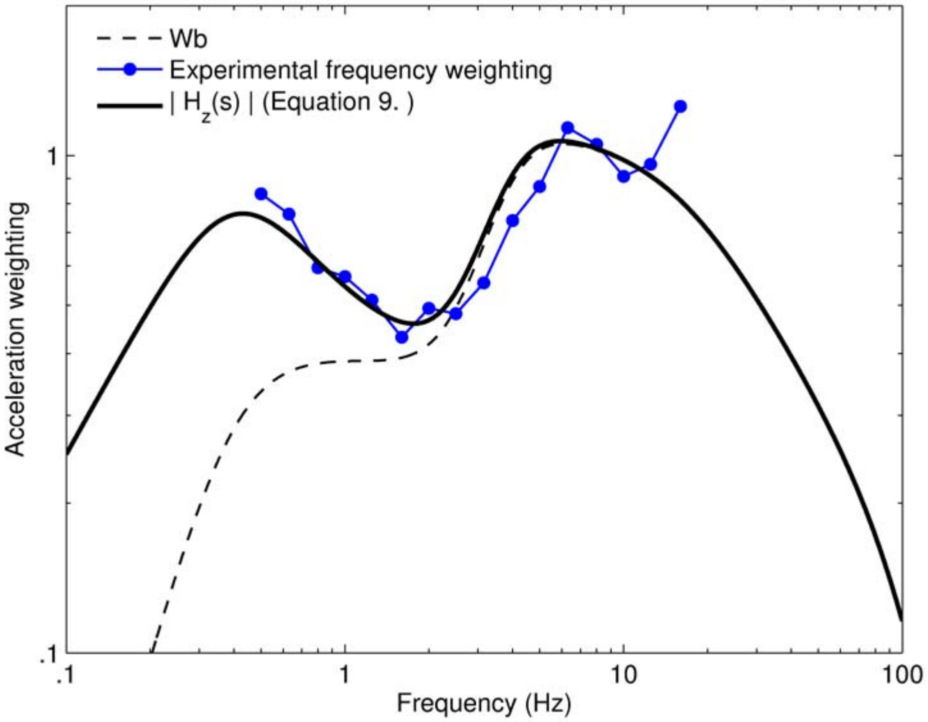


Figure 10.3: Comparison of the experimental frequency weighting for vertical vibration, the frequency weighting $W_b$ and the weighting constructed in Equation (10.7).

## 10.3.3 The effect of magnitude

### 10.3.3.1 Necessity of a corrected frequency weighting

It was shown in Section 9.2.3 that the shape of frequency weightings for vertical vibration depends on the magnitude of vibration. Despite this magnitude-dependence, in the present model a single frequency-weighting was used for each direction of vibration, regardless of the magnitude. This section presents a possible approach to this issue. It shows an example of a practical method for modifying the frequency weighting as a function of magnitude based on experimental results, which is not a systematic way of addressing the magnitude dependence of frequency weightings.

The frequency weighting defined in Section 10.3.2 was derived from an equivalent sensation contour corresponding to an estimate of '150' (with the particular reference magnitude and frequency of the experiment reported in Chapter 4). So, the frequency weighting $W_z(f) = |H_z(2\pi i f)|$ is expected to be suitable for the evaluation of vibration of similar subjective magnitudes. If, on the other hand, the magnitude of the vibration is significantly greater or less than 150, the weighting $W_z$ may not be suitable. A correction of the frequency weighting at low frequencies is necessary, resulting in a corrected weighting $W_\psi$ adapted to the evaluation of a motion of subjective magnitude $\psi$.

Equation (9.15) shows that the frequency weighting $W_\psi$ must be such that:

$$\frac{W_\psi(0.5\text{Hz})}{W_\psi(16\text{Hz})} = \left(\frac{\psi}{150}\right)^{\frac{1}{0.6}-\frac{1}{n_{0.5Hz}}} \frac{W_{150}(0.5\text{Hz})}{W_{150}(16\text{Hz})} \tag{10.8}$$

where $n_{0.5\text{Hz}} \approx 1.5$ (Table 4.7), so:

$$\frac{W_\psi(0.5\text{Hz})}{W_\psi(16\text{Hz})} = \left(\frac{\psi}{150}\right) \frac{W_{150}(0.5\text{Hz})}{W_{150}(16\text{Hz})} \tag{10.9}$$

No correction of the frequency weighting is necessary at 16 Hz, as the rate of growth of sensation ($n$) for 16-Hz vertical vibration was chosen arbitrarily as reference, and is similar to the rate of growth for horizontal vibration. Therefore, the corrected weighting $W_\psi$ must be such that:

$$W_\psi(16\,\text{Hz}) = W_z(16\,\text{Hz}) \tag{10.10}$$

$$W_\psi(0.5\,\text{Hz}) = \frac{\psi}{150} W_z(0.5\,\text{Hz}) \tag{10.11}$$

The correction may be achieved by multiplying the weighting introduced in Section 10.3.2 by a corrective weighting $W_{cor}$:

$$W_\psi(f) = W_{cor}(f)\, W_z(f) \tag{10.12}$$

Which is such that:

$$W_{cor}(0.5\,\text{Hz}) = \frac{\psi}{150} \tag{10.13}$$

As frequency increases from 0.5 to 5.0 Hz, the rate of growth of sensation, $n$, decreases and becomes gradually closer to the 0.6, which is the 'normal value' (i.e., the value the frequency-weighting model was based on - see Table 4.7 and Figure 4.5). So, the effect of vibration magnitude on vibration discomfort gradually becomes more similar to that over the frequency range from 5.0 to 16 Hz, which is arbitrarily chosen as the reference condition. Therefore, the weighting $W_{cor}$ must become gradually closer to 1 (i.e., no correction) as frequency increases from 0.5 to 5.0 Hz. In addition, the exponent $n$ is equal to the reference value over the range 5.0 to 16 Hz, so:

$$W_{cor}(f) = 1.0 \ , \ \ 5.0\,\text{Hz} < f < 16\,\text{Hz} \tag{10.14}$$

As shown in Equation (10.13), the approximate subjective magnitude of the signal, $\psi$, (with the reference used in the experiment) needs to be known to apply a correction to the weighting, as the magnitude of the correction depends on the magnitude of the vibration. The estimation of the subjective magnitude (compared to the reference used in the experiment in Chapter 4) is detailed in Section 10.3.3.2.

#### 10.3.3.2 Estimation of the subjective magnitude of the vibration

The frequency weighting $W_z$ proposed in Section 10.3.2 for vertical vibration is equal to 1.0 at about 5 Hz (see Figure 10.3). Therefore, the frequency weighting process using $W_z$ can be interpreted as an equivalent magnitude, which is the magnitude of 5-Hz vertical vibration that causes equivalent discomfort (see justification in Section 10.6.1). Therefore, the subjective magnitude of the vibration can be estimated as:

$$\psi = k_{5\text{Hz}} {a_w}^{n_{5\text{Hz}}} \tag{10.15}$$

where $k_{5\text{Hz}}$ and $n_{5\text{Hz}}$ are the constant and the exponent in Stevens' power law for 5-Hz vertical vibration, and $a_w$ is the frequency-weighted r.m.s acceleration. This equation is valid because the frequency weighting is equal to 1.0 at 5 Hz. The 'uncorrected' frequency weighting can be used in this first step in which an approximate estimate of the magnitude is sought. The median values for $k_{5\text{Hz}}$ and $n_{5\text{Hz}}$ were calculated in Chapter 4 and are equal to, respectively, 210 and 0.55.

To obtain an estmation of the subjective magnitude (for the determination of the correction to apply), the non-corrected frequency weighting $W_b$ can be used, as it is similar to the corrected weighting and only an estimate is needed.

#### 10.3.3.3 Corrected weighting

Practically, the correction is performed by multiplying the frequency weighting for vertical vibration $H_z$ by a corrective frequency weighting $W_{cor}$. As explained in Section 10.3.3.1, the corrective weighting must decrease as frequency increases from 0.5 to 5.0 Hz, and be equal to 1.0 in the range 5.0 to 16 Hz. The value at 0.5 Hz is $\frac{\psi}{150}$ (Equation 10.13), with the value of $\psi$ obtained as explained in Section 10.3.3.2. If $\psi > 150$, the following analogue filter satisfies these conditions, as shown in Figure 10.4:

$$W_c(f) = H_c^+(2\pi f) \tag{10.16}$$

where:

$$H_c^+(s) = \frac{{\omega_2}^2}{\omega_1} \frac{s+\omega_1}{s} \frac{s}{s^2 + 2\zeta\omega_2 s + {\omega_2}^2} \frac{s+\omega_3}{\omega_3} \tag{10.17}$$

and:

- $s = 2\pi i f$
- $\omega_j = 2\pi i f_j, j = 1..3$
- $f_1 = 0.25$ Hz
- $f_2 = 0.5$ Hz
- $f_3 = 1$ Hz
- $\zeta = \frac{1}{2Q}$
- $Q$ is a quality factor which must be adjusted depending on the desired gain at 0.5 Hz. The gain of the filter is shown for different values of $Q$ in Figure 10.4

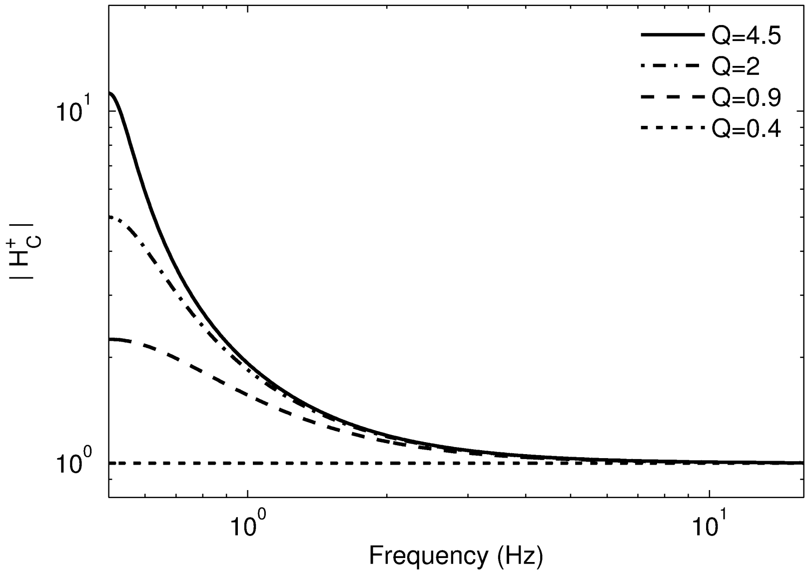


Figure 10.4: Gain of the filter defined in Equation (10.17) for different values of the quality factor $Q$.

The gain of the filter at 0.5 Hz depends on the value of the quality factor as follows:

$$\left|H_c^+(0.5\text{Hz})\right| = 2.5Q \tag{10.18}$$

So, $Q$ must be chosen so that:

$$Q = \frac{1}{2.5}\frac{\psi}{150} \tag{10.19}$$

If $\psi < 150$, the inverse filter can be used to decrease the value of the weighting at 0.5 Hz.

$$H_c^-(s) = \frac{1}{H_Q^+(s)} = \frac{\omega_1}{{\omega_2}^2}\frac{s}{s+\omega_1}\frac{s^2+2\zeta\omega_2 s+{\omega_2}^2}{s}\frac{\omega_3}{s+\omega_3} \tag{10.20}$$

where:

$$Q = \frac{1}{2.5}\frac{150}{\psi} \tag{10.21}$$

The corrected frequency weightings for $\psi$ equal to 75, 100, 150, and 200 are shown in Figure 10.5 and compared with the frequency weighting $W_b$.

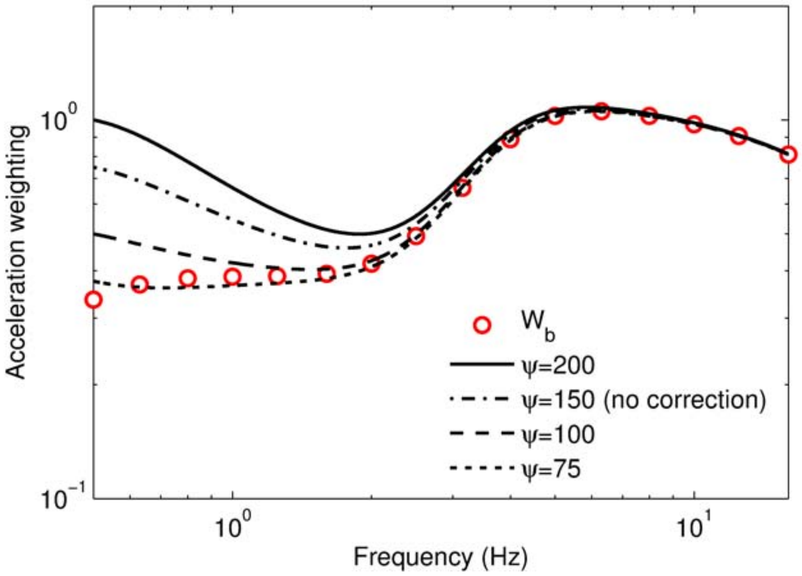


Figure 10.5: Corrected frequency weightings obtained at different subjective magnitude, and compared with the frequency weighting $W_b$.

## 10.4 Discomfort of people using body supports

In Chapter 6, additional frequency weightings representing the effect of postural supports were constructed. They are shown in Figure 10.6. In three conditions, the supports had a significant effect: when the subjects used a back support while exposed to fore-and-aft or lateral vibration, and when the subjects used a shoulder support while exposed to lateral vibration. Discomfort was increased in these conditions when the support created a new path for vibration to the upper body. The three supports that increased the discomfort can be modelled by analogue filters. In the two conditions where the supports transmit vibration directly to the body (back support with fore-and-aft vibration and shoulder support with lateral vibration), the weighting was equal to about 1 at lower frequencies (no effect) and was equal to about 3 at high frequencies. The transition frequency may depend on the support. On the other hand, with lateral vibration and a back support, vibration was transmitted to the upper body by friction. Degradation of comfort (and probably increased vibration transmission) seemed to happen particularly at 2 Hz. When frequency increased beyond 2 Hz, the effect was reduced, probably because as frequency increased, the effect of friction was reduced. Therefore, the effect of this support was modelled by a filter equal to 1.0 at the lowest and highest frequencies, and equal to about 2 at 2 Hz. On the other hand, with a backrest support and fore-and-aft vibration, or a shoulder support and lateral vibration, vibration will still be transmitted to the body at high frequencies, so the weighting should not decrease at higher frequencies.

In the study investigating the effect of supports (Chapter 6), the posture of subjects was fully determined (in particular, the distance between the feet and the supports), so the force applied on the support was controlled. In real applications, the force may be more or less than that used in the experiment. The effect of supports may depend on the force applied to the supports (probably increasing with increasing force).

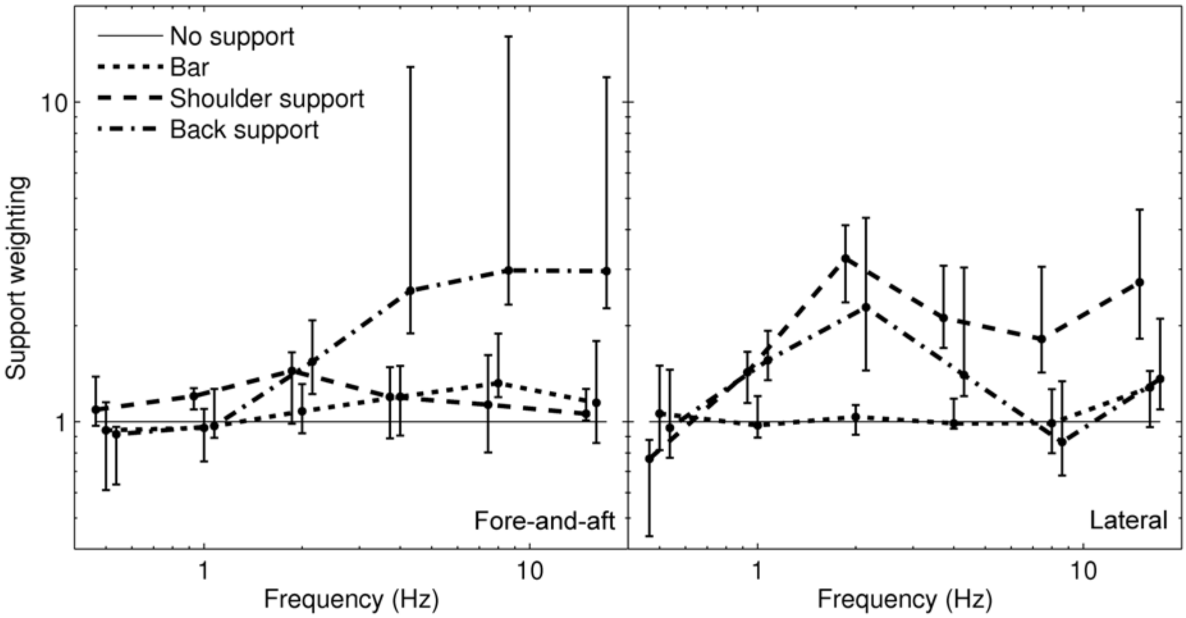


Figure 10.6: Support weightings determined in Chapter 6.

The three supports were modelled by analogue filters with the following transfer functions. The parameters were adjusted to obtain gains fitting the weightings obtained in the experiment (Figure 10.7).

$$H_{back,x}(s) = \frac{s^2 + 2\zeta_1\omega_{1,bx}s + \omega_{1,bx}{}^2}{\omega_{1,bx}{}^2} \frac{\omega_{2,bx}{}^2}{s^2 + 2\zeta_1\omega_{2,bx}s + \omega_{2,bx}{}^2} \tag{10.22}$$

$$H_{back,y}(s) = \frac{s + \omega_{1,by}}{s\omega_{1,by}} \frac{\omega_{2,by}{}^2 s}{s^2 + 2\zeta_2\omega_{2,by}s + \omega_{2,by}{}^2} \frac{s + \omega_{3,by}}{\omega_{3,by}} \tag{10.23}$$

$$H_{shoulder,y}(s) = \frac{s^2 + 2\zeta_1\omega_{1,sy}s + \omega_{1,sy}{}^2}{\omega_{1,sy}{}^2} \frac{\omega_{2,sy}{}^2}{s^2 + 2\zeta_1\omega_{2,sy}s + \omega_{2,sy}{}^2} \tag{10.24}$$

where angular frequencies are related with frequencies with the usual relation $\omega_j = 2\pi f_j$, and:

- $s = 2\pi i f$
- $\zeta_1 = 0.63$
- $\zeta_2 = 0.56$

- $f_{1,bx} = 1.8$ Hz , $f_{2,bx} = 3.1$ Hz
- $f_{1,sy} = 0.9$ Hz , $f_{1,sy} = 1.53$ Hz
- $f_{1,by} = 1.2$ Hz , $f_{2,by} = 2.4$ Hz , $f_{3,by} = 4.8$ Hz

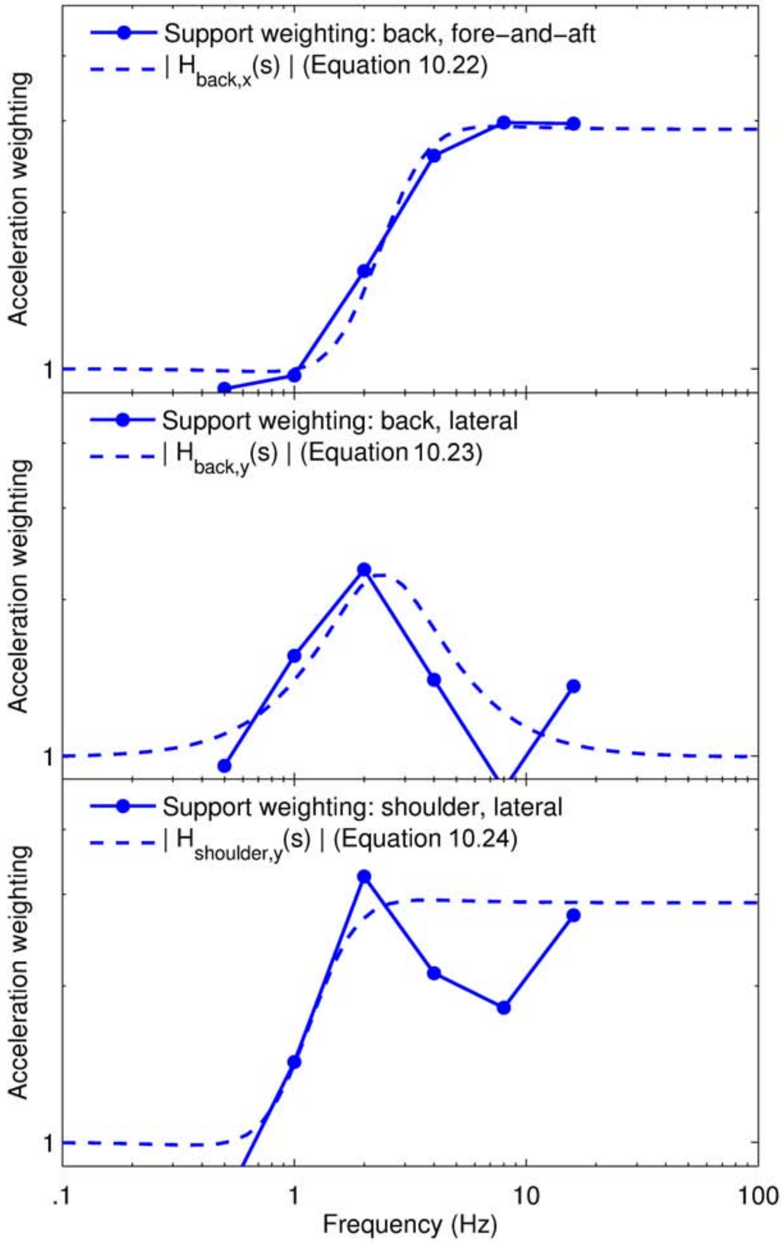


Figure 10.7: Support weightings for the three conditions where the support affected significantly discomfort, and analogue filters modelling the effect of supports (Equations 10.22, 10.23 and 10.24).

## 10.5 Evaluation of single-axis components of vibration

### 10.5.1 Evaluation of motions of the same duration

After the vibrations in the fore-and-aft, the lateral, and the vertical direction have been frequency-weighted, they may be evaluated. The evaluation of a vibration provides a single value representing the discomfort that it causes. In Chapter 7, it was found that when vibration may contain transients, the $rm_\lambda$ value could provide a non-biased estimation method (in the sense that it did not underestimate or overestimate the discomfort of peaky motions):

$$rm_\lambda = \left[ \frac{1}{T} \int_0^T |a(t)|^\lambda dt \right]^{1/\lambda} \tag{10.25}$$

The value of $\lambda$ for which the evaluation method was unbiased depended on frequency, and was approximately 3.0 at 1 Hz and 3.5 at 8 Hz.

If the frequency weightings introduced in Section 10.3 are used, the same exponent must be used at all frequencies, because using different exponents (provided it was practically possible) would introduce an artificial bias. This is due to the frequency weightings being devised assuming that the same measure (e.g., the r.m.s. value) applies at all frequencies. If the choice was made to use different exponents at different frequencies, the frequency weightings could be modified to take it into account.

When vibration is in the range 0 to 16 Hz, the value of 3.0 can be used as an average. It might underestimate some peaky motions at higher frequencies and underestimate motions at lower frequencies. For example, if $\lambda = 3.0$ is used, 8-Hz transients such as the motion shown in Figure 10.8.a (which is the most peaky waveform used in Chapter 7) will be evaluated as 1.20 times as uncomfortable as the sinusoidal motion shown in Figure 10.8.b (the least peaky motion possible):

$$\frac{rm_{3.0}(a_{(a)})}{rm_{3.0}(a_{(b)})} = 1.20 \tag{10.26}$$

According to the results of Chapter 7, a value of $\lambda = 3.5$ would be more appropriate, so the transient in Figure 10.8.a should be rated as 1.30 times as uncomfortable as the motion in Figure 10.8.b:

$$\frac{rm_{3.5}(a_{(a)})}{rm_{3.5}(a_{(b)})} = 1.30 \tag{10.27}$$

The difference between the evaluations with $\lambda = 3.5$ and $\lambda = 3.0$ is:

$$\frac{1.20}{1.30} = 0.92 \tag{10.28}$$

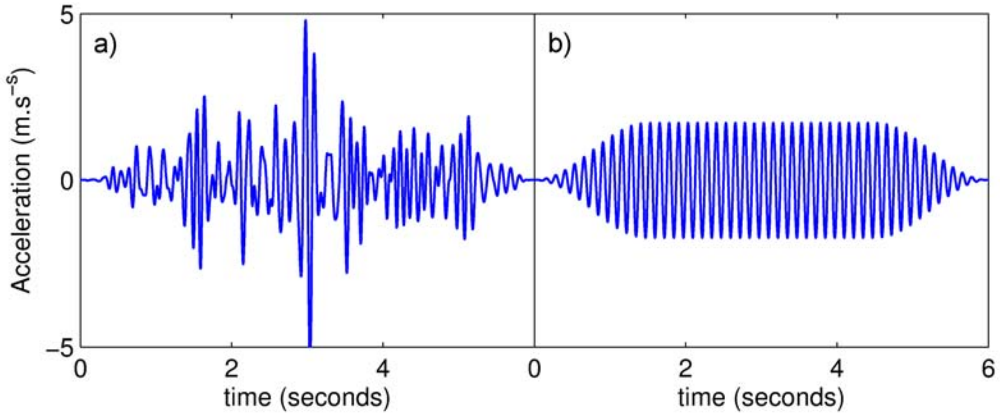


Figure 10.8: Most peaky and less peaky motions used in Chapter 7 (r.m.q./r.m.s. ratios are equal to 1.68 and 1.20 respectively). The two motions have the same r.m.s. value.

So, using a $\lambda$ value of 3.0 would lead to overestimating 8-Hz peaky motions by about 8%. Conversely, peaky vibration at frequencies less than 1 Hz would be slightly underestimated, so in the case of a broadband vibration the overestimation at higher frequencies may approximately offset the underestimation at lower frequencies. In this chapter, a model for comparing the discomfort of stimuli of the same duration is considered, so there is no difference between using a dose value (cumulative method) and the $rm_\lambda$ value (averaging method); the $rm_\lambda$ will be used.

### 10.5.2 The effect of duration

As mentioned in Section 10.1, since the effect of duration on discomfort was not investigated, the model does not apply to vibration of different durations. The model may be extended, based on results from previous studies with seated people. Griffin and Whitham (1980) showed that the discomfort of vibration of varying durations could be estimated using a dose value:

$$VD_\lambda = \left[ \int_0^T |a(t)|^\lambda \right]^{1/\lambda} \tag{10.29}$$

Only integer values of $\lambda$ were considered, and in all previous studies, values between 2 and 4 were found appropriate. Estimating the severity of the vibration with the $VD_3$ dose would therefore be in agreement with these results. So, the $VD_3$ dose could be used instead of the $rm_3$ value suggested in Chapter 7 and section 10.5.1. Such a modification would not essentially modify the model when applied to motions of the same duration, as the $VD_3$ dose value is proportional to the $rm_3$ value when the duration of motions is constant (Equation 10.31). With this modification, the model could be used to compare the discomfort caused by motions of different durations.

$$VD_3 = \left[ \int_0^T |a(t)|^3 \right]^{1/3} = \left[ T \frac{1}{T} \int_0^T |a(t)|^3 \right]^{1/3} = T^{1/3} \left[ \frac{1}{T} \int_0^T |a(t)|^3 \right]^{1/3} \tag{10.30}$$

$$\Rightarrow VD_3 = T^{1/3} rm_3(a) \tag{10.31}$$

## 10.6 Combining the discomfort in all three axes

### 10.6.1 Preliminary

The frequency-weighting procedure described in Section 10.3 produces weighted acceleration values for each direction of vibration, $a_x$, $a_y$ and $a_z$. These weighted values can also be interpreted as equivalent magnitudes. This means that they are the magnitudes of a vibration in a particular reference direction $D_0$ and at a particular frequency $f_0$ which produces equivalent comfort to, respectively, the fore-and-aft, lateral, and vertical components of the vibration. The reference condition (i.e., the direction $D_0$ and the frequency $f_0$) is a condition where the frequency weighting is equal to 1.0.

To justify this statement, let us suppose that the weighting for vibration in direction $D_0$ and at frequency $f_0$ is equal to 1.0

$$W(f_0, D_0) = 1.0 \tag{10.32}$$

and let us call the 'equivalent magnitude' of a vibration motion, the magnitude of a vibration in the direction $D_0$ and at frequency $f_0$ that would cause equivalent discomfort to the considered vibration.

Let us assume that vibration is presented with magnitude $a_1$ at a frequency $f$ and direction $D$ where the frequency weighting is equal to 2.0:

$$W(f, D) = 2.0 \tag{10.33}$$

The frequency weighting value of 2.0 means that people are twice as sensitive to vibration in the condition $(f, D)$ as in the condition $(f_0, D_0)$, where the weighting is equal to 1.0. This means that a vibration with magnitude $a_1$ in the condition $(f, D)$ causes equivalent discomfort as fore-and-aft vibration with magnitude $2a_1$ in the condition $(f_0, D_0)$. So, $2a_1$ is the equivalent magnitude for the considered motion.

When the frequency weighting is applied to the motion, the resulting weighted acceleration is $2a_1$ (because the weighting is equal to 2.0, as shown in Equation 10.33): it appears that it is equal to the equivalent magnitude. This justifies, in the case of a single-frequency vibration, that the weighted acceleration can be interpreted as an equivalent magnitude. This can be extended for vibration with a larger frequency spectrum.

At a frequency of 1 Hz, the weighting $W_x$ is equal to 1.0 (Figure 10.2); this means that weighted motions in all directions can be interpreted as equivalent magnitudes, with the reference being 1-Hz fore-and-aft vibration.

This implies, in particular, that the discomfort caused by a single-axis component (in any axis) of weighted magnitude $a_1$ is:

$$\psi = k_0 a_w^{n_0} \tag{10.34}$$

where $k_0$ and $n_0$ are the constant and the exponent in Stevens' power law for 1-Hz fore-and-aft vibration.

### 10.6.2 Axes summation

The results in Chapter 8 showed that the discomfort $\psi_{total}$ caused by a tri-axial vibration can be predicted with the relation:

$$\psi_{total} = \left({\psi_x}^3 + {\psi_y}^3 + {\psi_z}^3\right)^{1/3} \tag{10.35}$$

where $\psi_x$, $\psi_y$, and $\psi_z$ are, respectively, the subjective magnitudes of the fore-and-aft, the lateral, and the vertical components.

As explained in Section 10.6.1, the evaluation process for each single-axis component produces values that can be interpreted as equivalent magnitudes of 1-Hz fore-and-aft vibration (i.e., the magnitudes of fore-and-aft 1-Hz sinusoidal vibration producing equivalent discomfort). So, if the weighting and evaluation process yielded values $a_x$, $a_y$ and $a_z$ in the fore-and-aft, lateral and vertical directions respectively, these values can be interpreted as equivalent magnitudes and the subjective magnitude of the fore-and-aft component is equivalent to the subjective magnitude of a 1-Hz fore-and-aft vibration with magnitude $a_x$:

$$\psi_x = \psi_{x,eq} = k_0 {a_{w,x}}^{n_0} \tag{10.36}$$

where $k_0$ and $n_0$ are, respectively, the constant and the exponent (or growth rate) in Stevens' power law (Equation 3.2 in the Methods chapter) for 1-Hz fore-and-aft vibration.

Similarly:

$$\psi_y = \psi_{y,eq} = k_0 {a_y}^{n_0} \tag{10.37}$$

$$\psi_z = \psi_{z,eq} = k_0 {a_z}^{n_0} \tag{10.38}$$

As explained in Sections 9.2.3.2 and 9.2.3.4, the growth rate $n$ is assumed to be independent of frequency, and equal to 0.66, so it is assumed that $n_0 = 0.66$. Equation (10.35) becomes:

$$\psi_{total} = \left[\left(k_0 {a_x}^{0.66}\right)^3 + \left(k_0 {a_y}^{0.66}\right)^3 + \left(k_0 {a_z}^{0.66}\right)^3\right]^{1/3} \tag{10.39}$$

$$\psi_{total} = k_0 \left({a_x}^{2.0} + {a_y}^{2.0} + {a_z}^{2.0}\right)^{1/3} \tag{10.40}$$

$$\psi_{total} = k_0 \left[\left({a_x}^{2.0} + {a_y}^{2.0} + {a_z}^{2.0}\right)^{1/2}\right]^{0.67} \tag{10.41}$$

Therefore:

$$\psi_{total} = k_0 {a_{total}}^{n_0} \tag{10.42}$$

where:

$$a_{total} = \left({a_x}^{2.0} + {a_y}^{2.0} + {a_z}^{2.0}\right)^{1/2.0} \tag{10.43}$$

Equation (10.42) shows that the equivalent magnitude for the tri-axial vibration is equal to $a_{total}$; this equivalent magnitude can be estimated from the equivalent magnitudes in the three translational directions as shown in Equation (10.43). This value is an estimation of the discomfort caused by the multi-axial vibration stimulus (i.e. an evaluation of the stimulus).

## 10.7 Conclusion

Based on the results of the experiments reported in Chapters 4 to 8, a model was constructed to predict the average vibration discomfort of standing people. The model is summarized in Figure 10.9.

The model is able to provide an evaluation of tri-axial motions and a subjective comparison between tri-axial vibrations of the same duration. An attempt to address the problem of magnitude-dependence is shown, providing frequency weightings that depend on the magnitude of vibration.The model can extended to include the evaluation of motions of different durations.

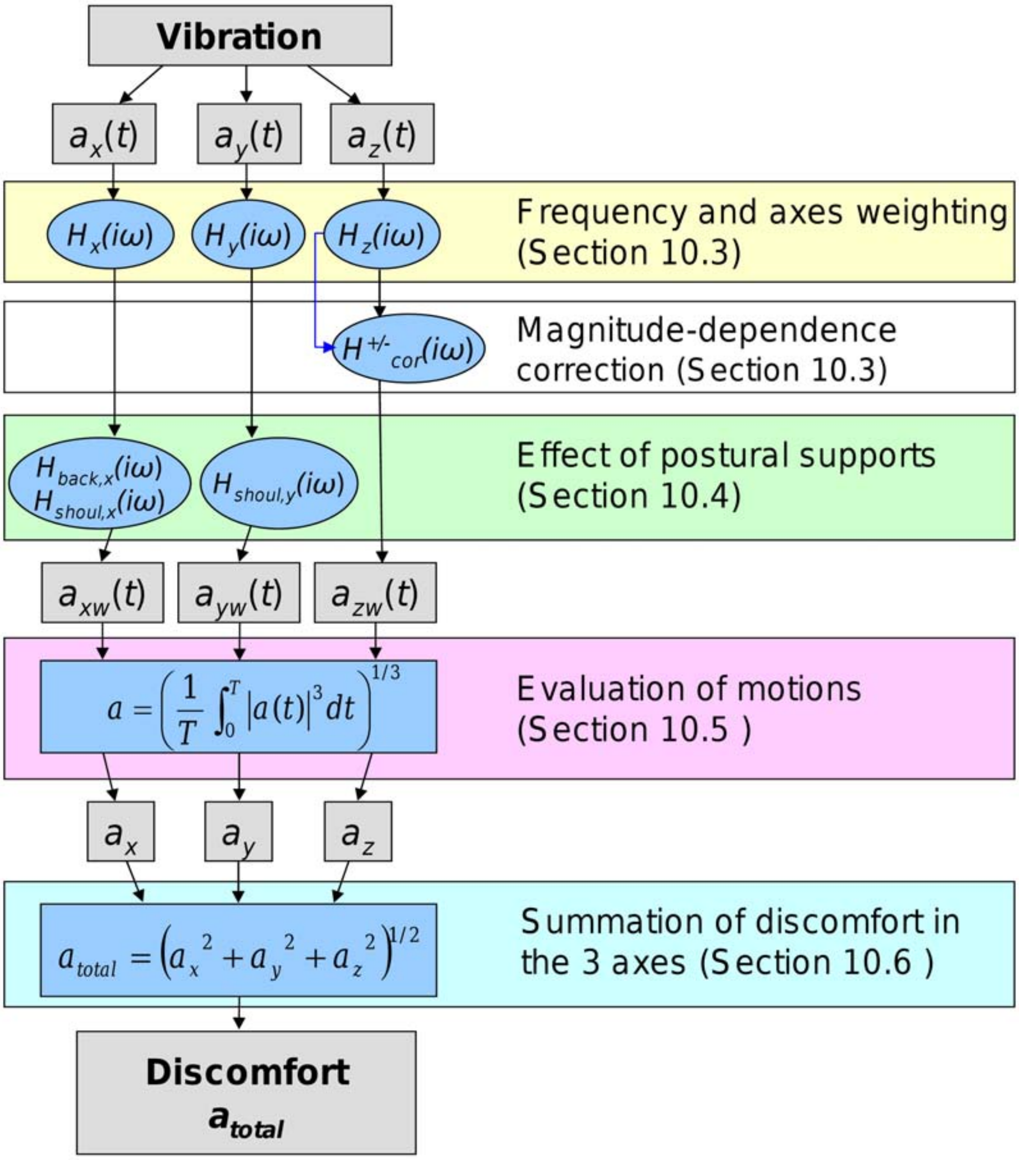


Figure 10.9: Predictive model.

# Chapter 11

# Conclusion

Five experiments have been conducted, investigating different aspects of the effects of vibration in the frequency range 0.5 to 16 Hz on the comfort of standing people (Chapters 4 to 8). The analysis of the results allowed the construction of a model showing the mechanisms of vibration discomfort in standing people (Chapter 9), and a predictive model that can be used to estimate the discomfort experienced by standing people exposed to simultaneous fore-and-aft, lateral, and vertical vibration (Chapter 10).

It appears that the main difference between the vibration discomfort of standing people and seated people lies in the frequency-dependence of the discomfort caused by horizontal vibration. The differences seemed to be due to different mechanisms being involved in the discomfort of standing and seated people exposed to horizontal vibration.

When exposed to low-frequency horizontal vibration, standing people experienced postural instability. In the frequency range where such instability was experienced (at frequencies between about 0.5 and 3.15 Hz for lateral vibration and between about 0.5 and 4 Hz for fore-and-aft vibration), sensitivity to vibration was determined by the vibration velocity (for seated people, sensitivity seems to be determined by acceleration over this frequency range).

At higher frequencies (3 to 16 Hz), the legs provide isolation, and little energy is transmitted from horizontal vibration of the floor to the upper body, contrary to seated subjects. As a result, no discomfort was experienced in the upper body by standing subjects in this frequency range. In this frequency range, discomfort was determined by vibration acceleration, whereas it seems to be determined by velocity in the case of seated people. The effects of fore-and-aft and lateral vibration were very similar, although fore-and-aft vibration appeared to cause more discomfort in the range 0.5 to 4 Hz, where fore-and-aft vibration causes more postural instability than lateral vibration.

The effect of the frequency of vertical vibration seems similar for standing and seated people.

Postural supports affected the vibration discomfort caused by horizontal vibration, due to their interaction with postural stability and the isolation effect of the legs. The supports that affected vibration discomfort were supports that were perpendicular to the direction of vibration and pushing the body during vibration: a back support with fore-and-aft vibration, and a lateral support with lateral vibration. These supports slightly reduced the discomfort caused by low-frequency vibration (about 0.5 Hz), probably because they helped subjects to keep their balance. At higher frequencies (greater than about 4 Hz), the supports increased discomfort, because they short-circuited the isolation effect of the legs.

Due to the different mechanisms involved in the causation of vibration discomfort, different methods are appropriate for the evaluation of vibration in terms of the discomfort of standing people and seated people. However, when optimal methods for the evaluation of motions containing transients and multi-axial vibration motions were constructed, based on experimental results, the findings were consistent with results obtained in previous studies with seated people. The results also suggested that the optimal evaluation method did not depend on the mechanisms, as no effect of direction was found despite different mechanisms being involved in the horizontal and vertical directions. It appears that motions containing transients can be estimated using a method similar to the root-mean-square and the root-mean-quad methods, but using an exponent of about 3.0 (instead of, respectively, 2 or 4). The discomfort caused by multi-axis vibration can be estimated by calculating the root-sum-of-cubes of the discomfort experienced when each of the single-axis translational components (fore-and-aft, lateral and vertical) is presented alone.

Based on these results, models of the vibration discomfort of standing people were constructed, including a predictive model that can be used to evaluate short-duration vibration in terms of the discomfort of standing people.

# Appendix A

# Instructions to subjects

## A.1 Experiment reported in Chapter 4

### A.1.1 Instruction sheet provided to the subjects

— General information —

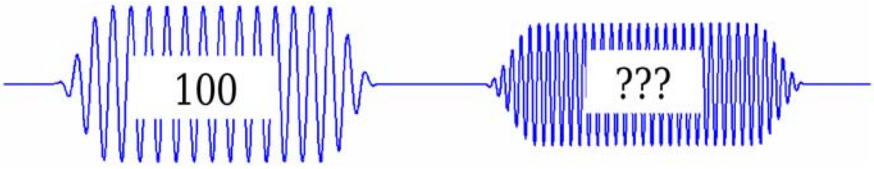
Thank you for your participation in the experiment. The aim of the experiment is to determine the effect of body supports on the discomfort caused by vibration. During the experiment, you will stand on a platform which will vibrate horizontally. A harness will prevent you from falling, in case of a loss of balance.

The experiment has been approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. During the experiment, you can stop the vibration at any moment, using the emergency stop button (red button) provided. You can quit the experiment anytime without providing a reason.

— Procedure —

You will be exposed to pairs of vibration stimuli (each stimuli lasting 6 s, with an interval of 2 s between them). The first stimulus is called reference, and will be identical throughout the experiment. After the exposure, you will be asked to **rate the discomfort caused by the second stimulus, assuming that the level of discomfort of the first stimulus is 100**.

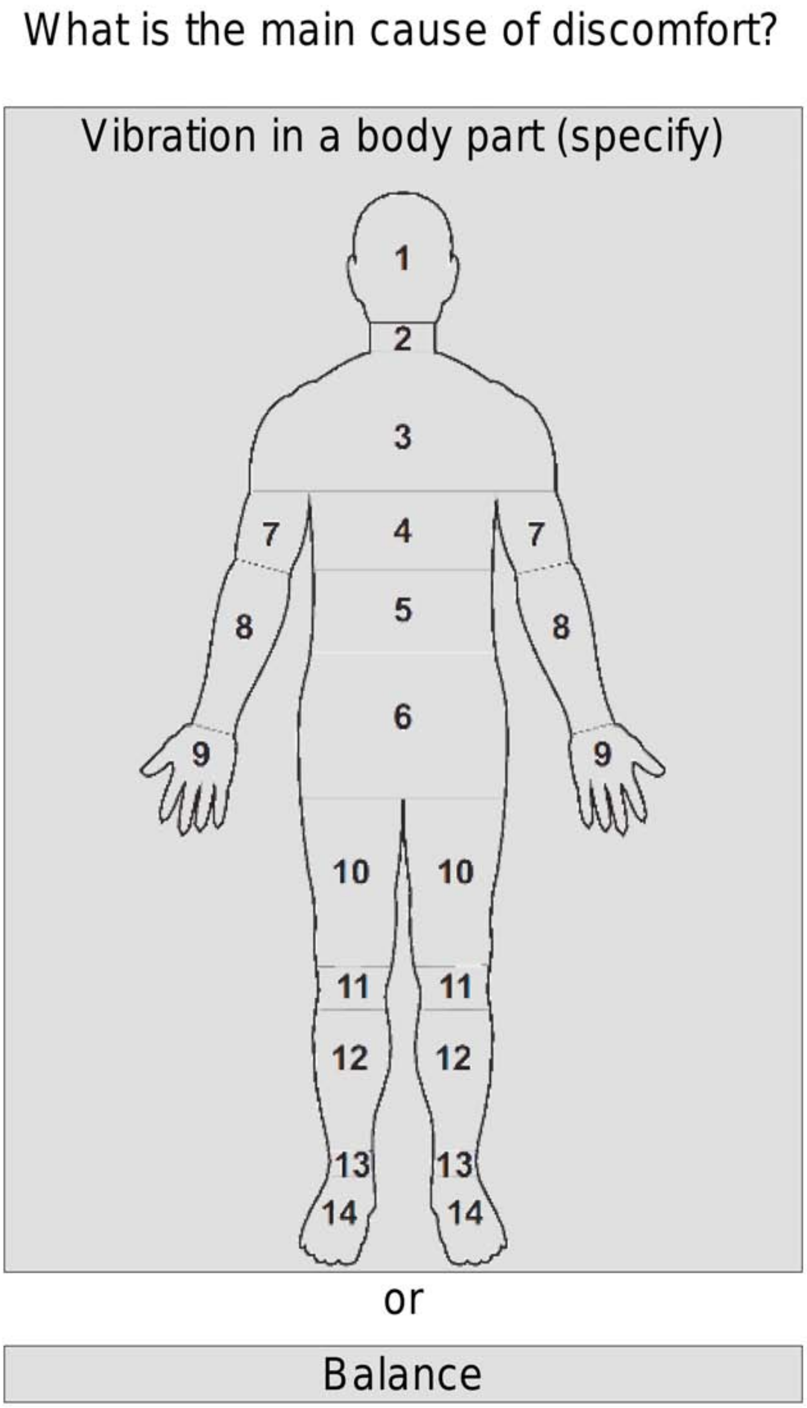
For example, if you feel that the second stimulus is about twice as uncomfortable as the first one, you should answer 200. If you feel that it is half as uncomfortable as the first one, an appropriate rating is 50. You can use **any number** as rating.



— Practice —

To practise the method of magnitude estimation, can you rate the length of the second line, assuming that the length of the first line is 100, for each pair of lines?

### A.1.2 Localization of discomfort: poster presented to the subjects (horizontal vibration)


What is the main cause of discomfort?

Vibration in a body part (specify)

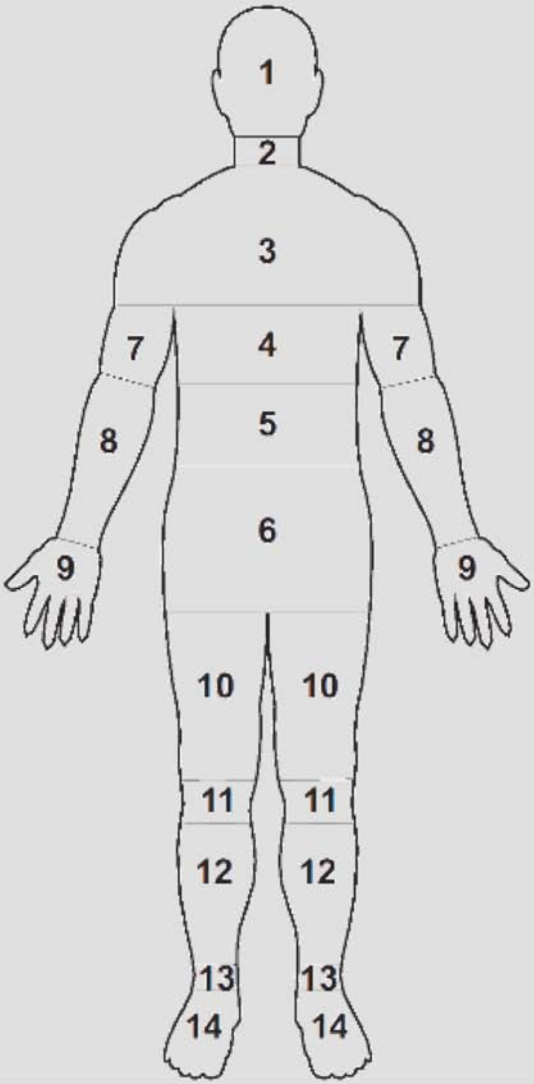
or

Balance

### A.1.3 Localization of discomfort: poster presented to the subjects (vertical vibration)

What is the main cause of discomfort?

Vibration in a body part (specify)



or

Other cause

## A.2 Experiment reported in Chapter 5

### A.2.1 Instruction sheet provided to the subjects

— General information —

Thank you for your participation in the experiment.

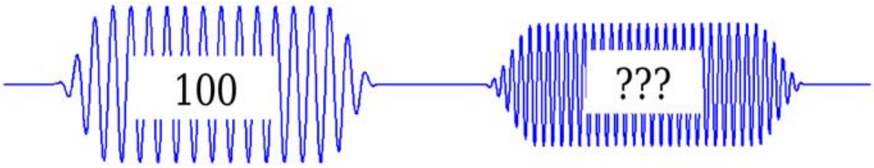
The aim of the experiment is to compare the discomfort caused by vibration in different directions. During the experiment, you will stand on a platform which will vibrate horizontally or vertically. A harness will prevent you from falling, in case of a loss of balance.

The experiment has been approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. During the experiment, you can stop the vibration at any moment, using the emergency stop button (red button) provided. You can quit the experiment anytime without providing a reason.

— Procedure —

You will be exposed to pairs of vibration stimuli which will be in different directions (each stimuli lasting 6 s, with an interval of 1 s between them). The first stimulus is called reference, and will be identical throughout the experiment. After the exposure, you will be asked to **rate the discomfort caused by the second stimulus, assuming that the level of discomfort of the first stimulus is 100**.

For example, if you feel that the second stimulus is about twice as uncomfortable as the first one, you should answer 200. If you feel that it is half as uncomfortable as the first one, an appropriate rating is 50. You can use **any number** as rating.



During the exposure, you will be asked to close your eyes
and stand in a normal upright position

— Pactice —

To practise the method of magnitude estimation, can you rate the length of the second line, assuming that the length of the first line is 100, for each pair of lines?

## A.3 Experiment reported in Chapter 6

### A.3.1 Instruction sheet provided to the subjects

—General information—

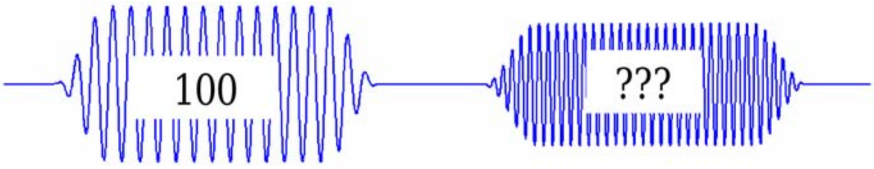
Thank you for your participation in the experiment. The aim of the experiment is to determine the effect of body supports on the discomfort caused by vibration. During the experiment, you will stand on a platform which will vibrate horizontally. A harness will prevent you from falling, in case of a loss of balance.

The experiment has been approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. During the experiment, you can stop the vibration at any moment, using the emergency stop button (red button) provided. You can quit the experiment anytime without providing a reason.

—Procedure—

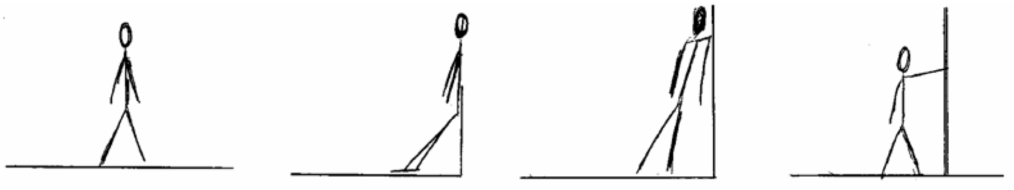
You will be exposed to pairs of vibration stimuli (each stimuli lasting 6 s, with an interval of 2 s between them). The first stimulus is called reference, and will be identical throughout the experiment. After the exposure, you will be asked to **rate the discomfort caused by the second stimulus, assuming that the level of discomfort of the first stimulus is 100.**

For example, if you feel that the second stimulus is about twice as uncomfortable as the first one, you should answer 200. If you feel that it is half as uncomfortable as the first one, an appropriate rating is 50. You can use **any number** as rating.



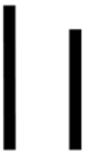
—Postures—

You will be asked to take four different postures during the experiment (see sketches below). At some point, you will have to change posture between the first and the second stimulus. Please follow the instructions given by the experimenter.



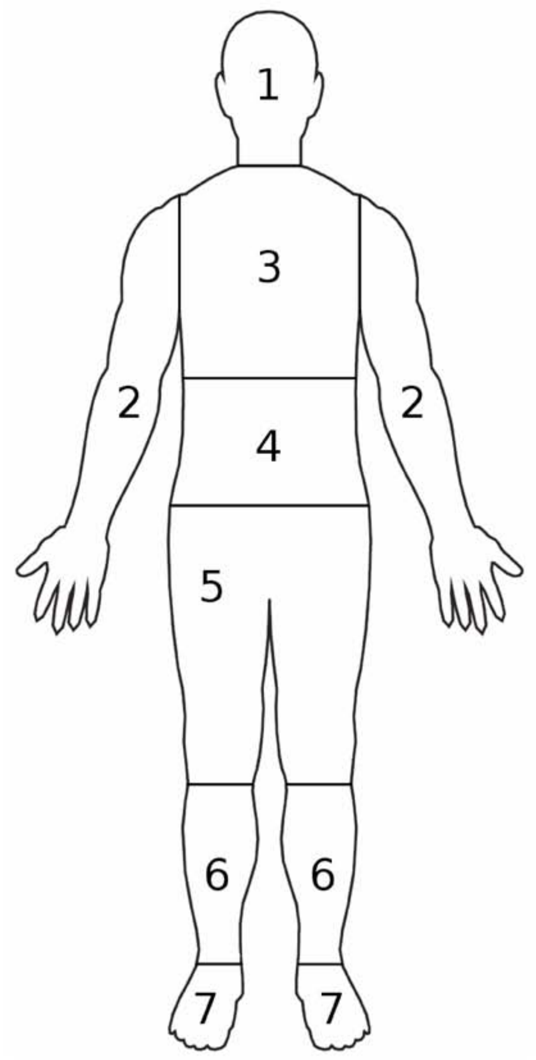
### —Practice—

To practise the method of magnitude estimation, can you rate the length of the second line, assuming that the length of the first line is 100, for each pair of lines?



### A.3.2 Localization of discomfort: poster presented to the subjects

Where in the body is the vibration most
uncomfortable?



## A.4 Experiment reported in Chapter 7

—General information—

Thank you for your participation in the experiment. The aim of the experiment is to determine the effect of random vibration motions on discomfort of standing train passengers.

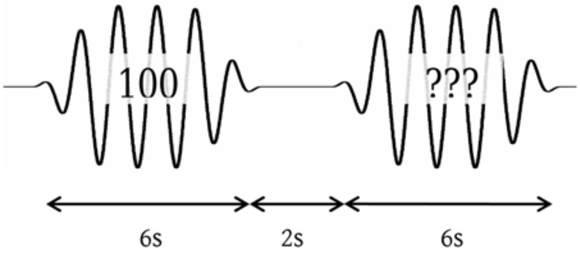
The experiment has been approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. During the experiment, you can stop the vibration at any moment, using the emergency stop button (red button) provided. You can quit the experiment anytime without providing a reason.

—Procedure—

During the experiment, you will be asked to:
- stand according to the marks on the floor,
- keep your knees locked
- keep your eyes closed, unless it becomes necessary to open them for safety

You will be exposed to pairs of vibration stimuli (each stimuli lasting 6 s, with an interval of 2 s between them). The first stimulus is called reference, and will be identical throughout the experiment. After the exposure, you will be asked to **rate the discomfort caused by the second stimulus, assuming that the level of discomfort of the first stimulus is 100**.

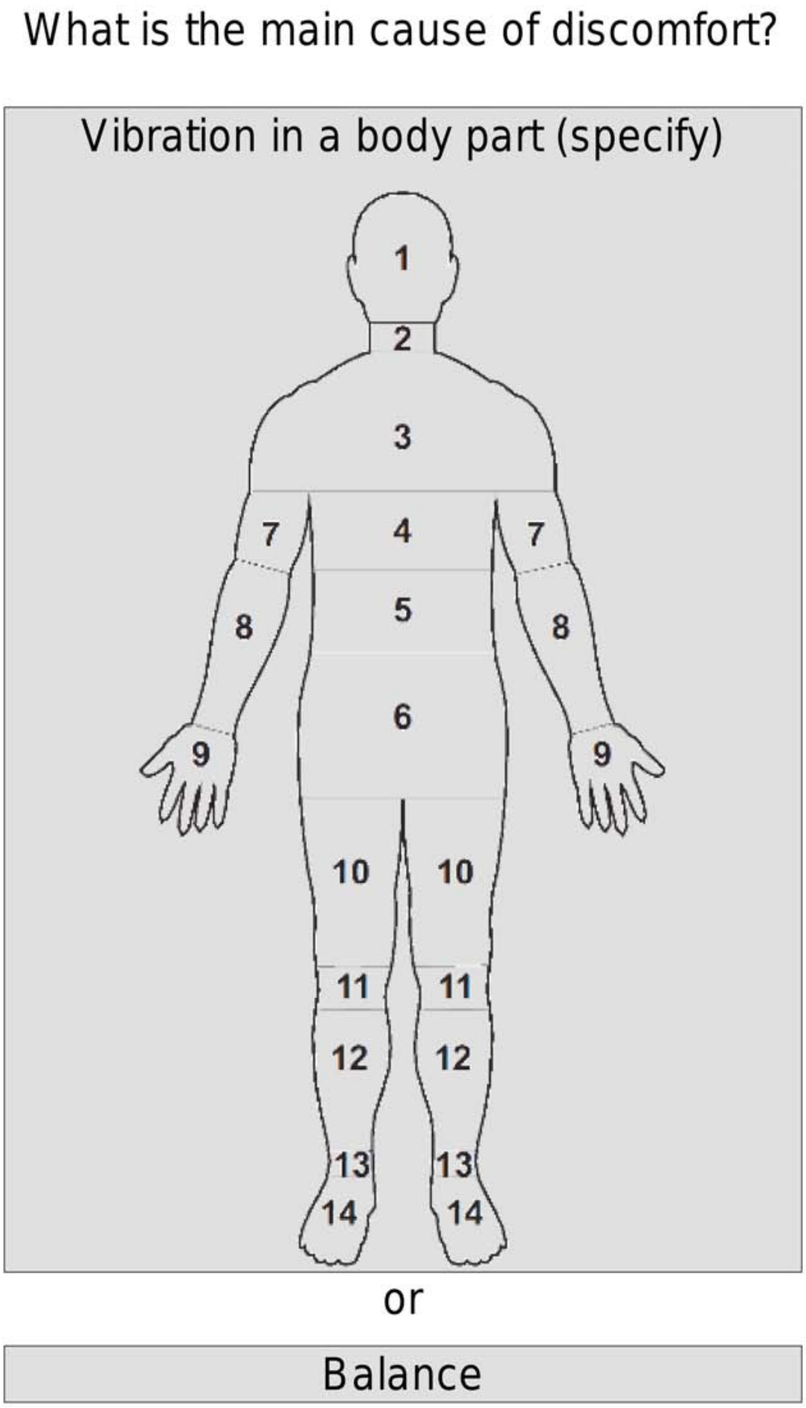
For example, if you feel that the second stimulus is about twice as uncomfortable as the first one, you should answer 200. If you feel that it is half as uncomfortable as the first one, an appropriate rating is 50. You can use **any number** as rating.



—Practice—

To practise the method of magnitude estimation, can you rate the length of the second line, assuming that the length of the first line is 100, for each pair of lines?

### A.4.1 Localization of discomfort: poster presented to the subjects (horizontal vibration)



What is the main cause of discomfort?

Vibration in a body part (specify)

or

Balance

### A.4.2 Localization of discomfort: poster presented to the subjects (vertical vibration)

What is the main cause of discomfort?

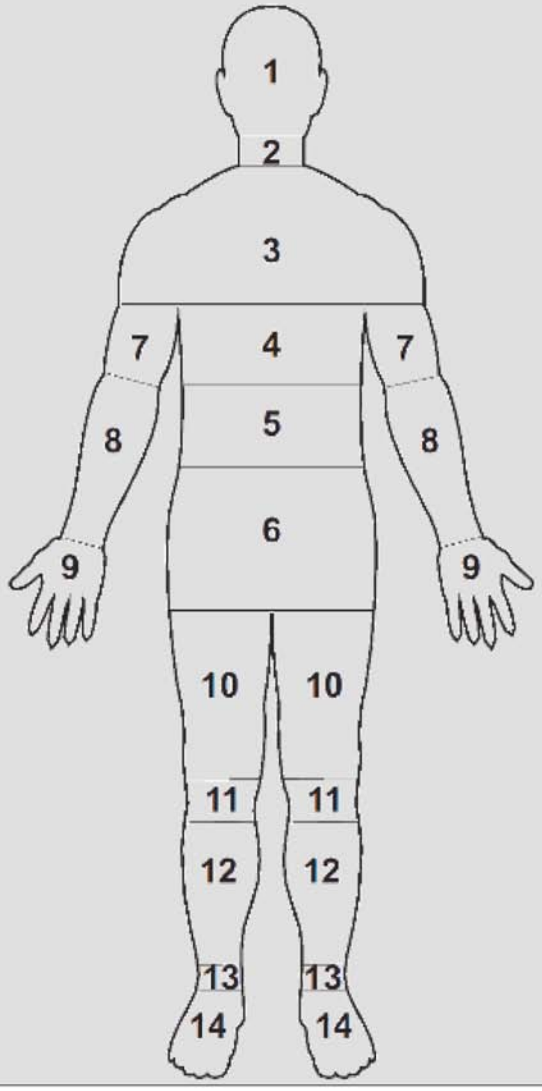
Balance

or

Dizziness

or

Vibration in a body part (specify)



## A.5 Experiment reported in Chapter 8

### A.5.1 Instruction sheet provided to the subjects

— General information —

Thank you for your participation in the experiment.

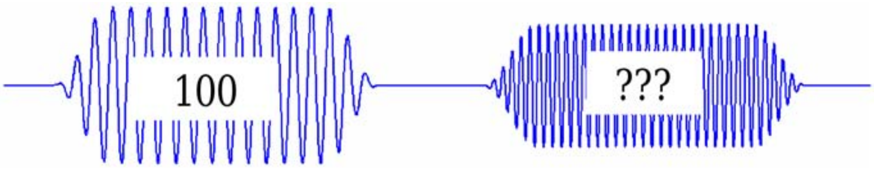
The aim of the experiment is to investigate the discomfort caused by vibration in several simulatenous directions. During the experiment, you will stand on a platform which will vibrate simultaneously horizontally and vertically. A harness will prevent you from falling, in case of a loss of balance.

The experiment has been approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. During the experiment, you can stop the vibration at any moment, using the emergency stop button (red button) provided. You can quit the experiment anytime without providing a reason.

— Procedure —

You will be exposed to pairs of vibration stimuli in all directions simultaneously (each stimuli lasting 6 s, with an interval of 1 s between them). The first stimulus is called reference. After the exposure, you will be asked to **rate the discomfort caused by the second stimulus, assuming that the level of discomfort of the first stimulus is 100**.

For example, if you feel that the second stimulus is about twice as uncomfortable as the first one, you should answer 200. If you feel that it is half as uncomfortable as the first one, an appropriate rating is 50. You can use **any number** as rating.



During the exposure, you will be asked to close your eyes
and stand in a normal upright position

— Pactice —

To practise the method of magnitude estimation, can you rate the length of the second line, assuming that the length of the first line is 100, for each pair of lines?

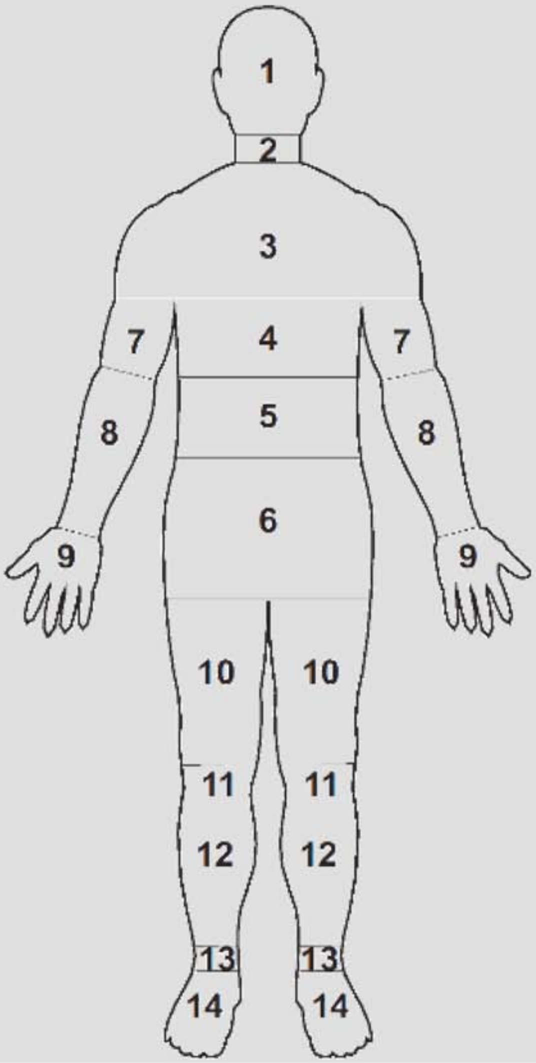
### A.5.2 Localization of discomfort: poster presented to the subjects

What is the main cause of discomfort?

Balance

or

Vibration in a body part (specify)



or

Other (specify)

# Appendix B

# Matlab script: Robust regression

The bisquare-weighted least square regression, called 'robust regression' in this thesis, was implemented in Matlab. The script of the function is included below. The number of iteration was fixed to 20; practically, preliminary tests showed that with typical examples the algorithm was converging after about 5 iterations.

This robust regression method is presented in Section 3.4.3 and by Fox (2002).

```
function out=robust(x,y)
    %number of iterations
    niter=20;

    %Initialization of the weights (uniform weights)
    weights=ones(size(x,1),size(x,2));

    for i=1:niter
        %parameters for the optimization
        Starting=[1 0];
        options=optimset('TolX',1e-8,'MaxIter',1000000,'MaxFunEval',1000000);

        %minimization of the weighted-sum-of-squares function (defined as a
        %sub-fonction below, using the current weights
        Estimates=fminsearch(@WSS,Starting,options,x,y,weights);

        %calculation of the residual of the optimization to determine the cutoff
        residual=y-Estimates(1)*x-Estimates(2);
        cutoff=6.9459 * median(abs(residual));

        %definition of new weights (bisquare weights)
        weights=(1-min(1,abs(res)/cutoff).^2).^2;
    end
end

function out=WSS(params,input,output,weights)
    %Weighted Sum of Squares = the function to minimize
    out=sum((output-params(1)*input-params(2)).^2.*weights);
end
```

# Appendix C

# Raw data

In this section, raw data obtained in Chapters 4 to 8 with the method of magnitude estimation are summarized.

## C.1 Chapter 4

Table C.1: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Fore-and-aft vibration, part 1/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 0.5 | 1 | 4 | 9 | 18 | 29 | 70 |
| 0.5 | 2 | 9 | 16 | 38 | 77 | 139 |
| 0.5 | 3 | 9 | 29 | 46 | 75 | 118 |
| 0.5 | 4 | 27 | 49 | 68 | 123 | 227 |
| 0.5 | 5 | 9 | 72 | 93 | 118 | 300 |
| 0.5 | 6 | 48 | 94 | 111 | 142 | 243 |
| 0.5 | 7 | 57 | 112 | 133 | 165 | 222 |
| 0.5 | 8 | 49 | 143 | 157 | 178 | 334 |
| 0.5 | 9 | 49 | 152 | 190 | 248 | 304 |
| 0.63 | 1 | 1 | 26 | 41 | 58 | 95 |
| 0.63 | 2 | 4 | 9 | 29 | 42 | 95 |
| 0.63 | 3 | 4 | 44 | 51 | 81 | 123 |
| 0.63 | 4 | 29 | 63 | 74 | 81 | 129 |
| 0.63 | 5 | 45 | 74 | 82 | 109 | 137 |
| 0.63 | 6 | 68 | 86 | 126 | 148 | 178 |
| 0.63 | 7 | 68 | 113 | 125 | 181 | 250 |
| 0.63 | 8 | 59 | 107 | 143 | 182 | 288 |
| 0.63 | 9 | 71 | 140 | 183 | 204 | 341 |
| 0.8 | 1 | 1 | 10 | 23 | 38 | 107 |
| 0.8 | 2 | 1 | 16 | 23 | 49 | 96 |
| 0.8 | 3 | 9 | 19 | 47 | 78 | 239 |
| 0.8 | 4 | 31 | 39 | 58 | 82 | 153 |
| 0.8 | 5 | 28 | 52 | 78 | 103 | 200 |
| 0.8 | 6 | 58 | 89 | 111 | 144 | 175 |
| 0.8 | 7 | 66 | 94 | 118 | 144 | 233 |
| 0.8 | 8 | 80 | 130 | 174 | 214 | 272 |
| 0.8 | 9 | 75 | 132 | 145 | 167 | 338 |
| 1 | 1 | 5 | 16 | 29 | 39 | 73 |
| 1 | 2 | 5 | 18 | 32 | 49 | 87 |
| 1 | 3 | 5 | 43 | 63 | 87 | 112 |
| 1 | 4 | 5 | 61 | 77 | 86 | 115 |
| 1 | 5 | 10 | 47 | 76 | 87 | 117 |
| 1 | 6 | 49 | 101 | 110 | 152 | 181 |
| 1 | 7 | 69 | 107 | 117 | 144 | 224 |
| 1 | 8 | 69 | 108 | 139 | 174 | 291 |
| 1 | 9 | 48 | 144 | 162 | 225 | 267 |

Table C.2: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Fore-and-aft vibration, part 2/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 1.25 | 1 | 3 | 9 | 23 | 42 | 126 |
| 1.25 | 2 | 10 | 18 | 30 | 58 | 76 |
| 1.25 | 3 | 5 | 33 | 56 | 79 | 119 |
| 1.25 | 4 | 27 | 45 | 71 | 95 | 124 |
| 1.25 | 5 | 48 | 79 | 96 | 101 | 128 |
| 1.25 | 6 | 27 | 65 | 94 | 113 | 169 |
| 1.25 | 7 | 78 | 95 | 107 | 134 | 221 |
| 1.25 | 8 | 59 | 115 | 146 | 184 | 265 |
| 1.25 | 9 | 72 | 142 | 157 | 172 | 242 |
| 1.6 | 1 | 1 | 8 | 12 | 40 | 68 |
| 1.6 | 2 | 1 | 15 | 29 | 58 | 89 |
| 1.6 | 3 | 9 | 47 | 58 | 77 | 128 |
| 1.6 | 4 | 18 | 58 | 76 | 93 | 101 |
| 1.6 | 5 | 29 | 74 | 84 | 104 | 144 |
| 1.6 | 6 | 66 | 77 | 103 | 116 | 487 |
| 1.6 | 7 | 88 | 109 | 117 | 134 | 193 |
| 1.6 | 8 | 76 | 128 | 138 | 181 | 219 |
| 1.6 | 9 | 109 | 139 | 164 | 194 | 229 |
| 2 | 1 | 2 | 9 | 18 | 37 | 59 |
| 2 | 2 | 9 | 29 | 45 | 70 | 79 |
| 2 | 3 | 9 | 19 | 38 | 49 | 94 |
| 2 | 4 | 9 | 72 | 89 | 97 | 132 |
| 2 | 5 | 10 | 88 | 93 | 96 | 120 |
| 2 | 6 | 77 | 97 | 103 | 109 | 118 |
| 2 | 7 | 95 | 109 | 123 | 140 | 226 |
| 2 | 8 | 96 | 114 | 152 | 165 | 241 |
| 2 | 9 | 75 | 141 | 167 | 179 | 234 |
| 2.5 | 1 | 1 | 9 | 28 | 44 | 57 |
| 2.5 | 2 | 1 | 10 | 25 | 48 | 80 |
| 2.5 | 3 | 9 | 61 | 80 | 97 | 118 |
| 2.5 | 4 | 30 | 72 | 92 | 97 | 113 |
| 2.5 | 5 | 81 | 90 | 96 | 99 | 119 |
| 2.5 | 6 | 68 | 91 | 100 | 115 | 244 |
| 2.5 | 7 | 67 | 99 | 116 | 126 | 174 |
| 2.5 | 8 | 88 | 117 | 142 | 179 | 203 |
| 2.5 | 9 | 77 | 129 | 175 | 192 | 291 |

Table C.3: Summary (minimum, 25th percentile, median, 75th percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Fore-and-aft vibration, part 3/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 3.15 | 1 | 1 | 9 | 22 | 49 | 78 |
| 3.15 | 2 | 9 | 26 | 50 | 75 | 93 |
| 3.15 | 3 | 36 | 66 | 87 | 95 | 122 |
| 3.15 | 4 | 9 | 85 | 93 | 100 | 125 |
| 3.15 | 5 | 20 | 95 | 105 | 124 | 148 |
| 3.15 | 6 | 74 | 104 | 118 | 153 | 206 |
| 3.15 | 7 | 79 | 105 | 122 | 142 | 183 |
| 3.15 | 8 | 77 | 118 | 147 | 167 | 181 |
| 3.15 | 9 | 105 | 140 | 176 | 203 | 286 |
| 4 | 1 | 5 | 18 | 47 | 56 | 87 |
| 4 | 2 | 9 | 36 | 48 | 84 | 107 |
| 4 | 3 | 53 | 74 | 87 | 107 | 116 |
| 4 | 4 | 37 | 68 | 90 | 115 | 128 |
| 4 | 5 | 79 | 100 | 117 | 128 | 178 |
| 4 | 6 | 51 | 108 | 119 | 134 | 198 |
| 4 | 7 | 61 | 118 | 141 | 176 | 216 |
| 4 | 8 | 87 | 140 | 177 | 202 | 243 |
| 4 | 9 | 105 | 164 | 187 | 245 | 282 |
| 5 | 1 | 5 | 48 | 75 | 83 | 143 |
| 5 | 2 | 19 | 55 | 85 | 104 | 119 |
| 5 | 3 | 44 | 72 | 96 | 115 | 137 |
| 5 | 4 | 54 | 82 | 111 | 116 | 145 |
| 5 | 5 | 45 | 112 | 119 | 140 | 176 |
| 5 | 6 | 96 | 114 | 134 | 156 | 196 |
| 5 | 7 | 99 | 147 | 169 | 183 | 230 |
| 5 | 8 | 112 | 143 | 176 | 192 | 273 |
| 5 | 9 | 98 | 173 | 189 | 204 | 277 |
| 6.3 | 1 | 19 | 40 | 60 | 89 | 203 |
| 6.3 | 2 | 18 | 56 | 82 | 109 | 181 |
| 6.3 | 3 | 41 | 53 | 101 | 120 | 178 |
| 6.3 | 4 | 30 | 76 | 117 | 139 | 184 |
| 6.3 | 5 | 49 | 89 | 113 | 139 | 153 |
| 6.3 | 6 | 72 | 114 | 144 | 179 | 224 |
| 6.3 | 7 | 76 | 116 | 147 | 179 | 264 |
| 6.3 | 8 | 79 | 143 | 178 | 190 | 216 |
| 6.3 | 9 | 68 | 159 | 185 | 202 | 312 |

Table C.4: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Fore-and-aft vibration, part 3/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 8 | 1 | 5 | 36 | 70 | 111 | 181 |
| 8 | 2 | 20 | 72 | 100 | 112 | 166 |
| 8 | 3 | 5 | 47 | 107 | 121 | 217 |
| 8 | 4 | 45 | 86 | 109 | 129 | 267 |
| 8 | 5 | 75 | 95 | 122 | 152 | 227 |
| 8 | 6 | 47 | 100 | 123 | 151 | 246 |
| 8 | 7 | 49 | 109 | 135 | 177 | 225 |
| 8 | 8 | 29 | 139 | 167 | 189 | 269 |
| 8 | 9 | 58 | 143 | 177 | 186 | 356 |
| 10 | 1 | 5 | 36 | 84 | 114 | 133 |
| 10 | 2 | 9 | 51 | 86 | 120 | 201 |
| 10 | 3 | 39 | 68 | 109 | 127 | 216 |
| 10 | 4 | 10 | 91 | 118 | 140 | 195 |
| 10 | 5 | 10 | 95 | 116 | 151 | 264 |
| 10 | 6 | 66 | 114 | 135 | 167 | 314 |
| 10 | 7 | 30 | 127 | 144 | 177 | 285 |
| 10 | 8 | 40 | 135 | 174 | 201 | 361 |
| 10 | 9 | 19 | 158 | 196 | 233 | 312 |
| 12.5 | 1 | 5 | 41 | 78 | 106 | 183 |
| 12.5 | 2 | 4 | 64 | 103 | 121 | 183 |
| 12.5 | 3 | 5 | 58 | 126 | 139 | 185 |
| 12.5 | 4 | 29 | 86 | 125 | 151 | 312 |
| 12.5 | 5 | 9 | 102 | 138 | 170 | 315 |
| 12.5 | 6 | 41 | 88 | 149 | 182 | 316 |
| 12.5 | 7 | 19 | 117 | 161 | 194 | 320 |
| 12.5 | 8 | 10 | 129 | 176 | 207 | 354 |
| 12.5 | 9 | 5 | 133 | 182 | 231 | 424 |
| 16 | 1 | 5 | 55 | 82 | 111 | 228 |
| 16 | 2 | 9 | 72 | 95 | 124 | 266 |
| 16 | 3 | 28 | 67 | 133 | 151 | 247 |
| 16 | 4 | 30 | 71 | 149 | 186 | 198 |
| 16 | 5 | 5 | 87 | 140 | 178 | 304 |
| 16 | 6 | 39 | 102 | 163 | 207 | 298 |
| 16 | 7 | 5 | 131 | 175 | 249 | 374 |
| 16 | 8 | 10 | 131 | 201 | 254 | 395 |
| 16 | 9 | 15 | 162 | 199 | 267 | 395 |

Table C.5: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Lateral vibration, part 1/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 0.5 | 1 | 10 | 20 | 34 | 49 | 125 |
| 0.5 | 2 | 4 | 20 | 49 | 83 | 119 |
| 0.5 | 3 | 15 | 45 | 65 | 93 | 137 |
| 0.5 | 4 | 12 | 49 | 72 | 96 | 145 |
| 0.5 | 5 | 48 | 80 | 102 | 117 | 196 |
| 0.5 | 6 | 59 | 101 | 117 | 131 | 200 |
| 0.5 | 7 | 82 | 109 | 135 | 176 | 309 |
| 0.5 | 8 | 74 | 111 | 149 | 190 | 311 |
| 0.5 | 9 | 90 | 143 | 179 | 248 | 297 |
| 0.63 | 1 | 5 | 26 | 43 | 51 | 156 |
| 0.63 | 2 | 5 | 27 | 43 | 77 | 117 |
| 0.63 | 3 | 19 | 52 | 65 | 84 | 136 |
| 0.63 | 4 | 39 | 66 | 84 | 109 | 149 |
| 0.63 | 5 | 18 | 61 | 81 | 117 | 205 |
| 0.63 | 6 | 61 | 110 | 135 | 144 | 202 |
| 0.63 | 7 | 69 | 118 | 126 | 169 | 302 |
| 0.63 | 8 | 78 | 107 | 128 | 165 | 207 |
| 0.63 | 9 | 50 | 139 | 156 | 204 | 340 |
| 0.8 | 1 | 5 | 18 | 23 | 42 | 118 |
| 0.8 | 2 | 20 | 31 | 60 | 74 | 117 |
| 0.8 | 3 | 20 | 30 | 54 | 92 | 154 |
| 0.8 | 4 | 29 | 70 | 85 | 97 | 114 |
| 0.8 | 5 | 20 | 79 | 104 | 121 | 197 |
| 0.8 | 6 | 40 | 109 | 119 | 134 | 204 |
| 0.8 | 7 | 76 | 98 | 113 | 132 | 183 |
| 0.8 | 8 | 49 | 122 | 144 | 159 | 233 |
| 0.8 | 9 | 73 | 125 | 145 | 177 | 224 |
| 1 | 1 | 5 | 17 | 35 | 58 | 145 |
| 1 | 2 | 5 | 39 | 50 | 71 | 95 |
| 1 | 3 | 9 | 37 | 50 | 70 | 107 |
| 1 | 4 | 48 | 64 | 106 | 121 | 132 |
| 1 | 5 | 29 | 87 | 95 | 99 | 129 |
| 1 | 6 | 49 | 82 | 104 | 113 | 170 |
| 1 | 7 | 76 | 112 | 124 | 140 | 280 |
| 1 | 8 | 51 | 117 | 131 | 162 | 200 |
| 1 | 9 | 98 | 126 | 146 | 171 | 201 |

Table C.6: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Lateral vibration, part 2/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 1.25 | 1 | 1 | 18 | 30 | 49 | 182 |
| 1.25 | 2 | 5 | 29 | 50 | 83 | 140 |
| 1.25 | 3 | 18 | 46 | 63 | 91 | 131 |
| 1.25 | 4 | 46 | 64 | 80 | 88 | 150 |
| 1.25 | 5 | 37 | 50 | 93 | 121 | 158 |
| 1.25 | 6 | 39 | 78 | 96 | 111 | 148 |
| 1.25 | 7 | 49 | 108 | 114 | 140 | 155 |
| 1.25 | 8 | 51 | 116 | 125 | 181 | 202 |
| 1.25 | 9 | 104 | 128 | 145 | 193 | 301 |
| 1.6 | 1 | 7 | 16 | 20 | 57 | 125 |
| 1.6 | 2 | 5 | 10 | 43 | 53 | 88 |
| 1.6 | 3 | 16 | 40 | 49 | 70 | 107 |
| 1.6 | 4 | 40 | 71 | 86 | 100 | 192 |
| 1.6 | 5 | 25 | 83 | 96 | 102 | 111 |
| 1.6 | 6 | 46 | 95 | 103 | 138 | 151 |
| 1.6 | 7 | 68 | 105 | 121 | 132 | 206 |
| 1.6 | 8 | 101 | 119 | 142 | 167 | 241 |
| 1.6 | 9 | 112 | 133 | 148 | 155 | 204 |
| 2 | 1 | 5 | 13 | 20 | 48 | 143 |
| 2 | 2 | 10 | 27 | 51 | 76 | 111 |
| 2 | 3 | 10 | 41 | 54 | 73 | 95 |
| 2 | 4 | 20 | 77 | 99 | 101 | 111 |
| 2 | 5 | 53 | 87 | 98 | 101 | 126 |
| 2 | 6 | 70 | 91 | 100 | 107 | 122 |
| 2 | 7 | 89 | 99 | 120 | 128 | 214 |
| 2 | 8 | 98 | 112 | 135 | 150 | 314 |
| 2 | 9 | 110 | 136 | 155 | 173 | 269 |
| 2.5 | 1 | 1 | 10 | 20 | 50 | 121 |
| 2.5 | 2 | 10 | 28 | 48 | 52 | 148 |
| 2.5 | 3 | 19 | 49 | 78 | 92 | 100 |
| 2.5 | 4 | 19 | 85 | 95 | 98 | 119 |
| 2.5 | 5 | 90 | 97 | 100 | 110 | 128 |
| 2.5 | 6 | 91 | 99 | 105 | 120 | 152 |
| 2.5 | 7 | 68 | 111 | 119 | 142 | 163 |
| 2.5 | 8 | 104 | 120 | 136 | 157 | 201 |
| 2.5 | 9 | 78 | 125 | 149 | 181 | 232 |

Table C.7: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Lateral vibration, part 3/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 3.15 | 1 | 9 | 11 | 28 | 46 | 80 |
| 3.15 | 2 | 9 | 37 | 64 | 86 | 98 |
| 3.15 | 3 | 20 | 67 | 88 | 102 | 114 |
| 3.15 | 4 | 39 | 75 | 98 | 110 | 131 |
| 3.15 | 5 | 81 | 97 | 111 | 115 | 149 |
| 3.15 | 6 | 59 | 116 | 135 | 153 | 223 |
| 3.15 | 7 | 76 | 100 | 119 | 145 | 182 |
| 3.15 | 8 | 99 | 117 | 138 | 153 | 296 |
| 3.15 | 9 | 105 | 130 | 159 | 183 | 243 |
| 4 | 1 | 5 | 12 | 34 | 71 | 86 |
| 4 | 2 | 9 | 23 | 41 | 71 | 110 |
| 4 | 3 | 10 | 45 | 72 | 100 | 147 |
| 4 | 4 | 10 | 49 | 99 | 111 | 119 |
| 4 | 5 | 61 | 98 | 113 | 134 | 172 |
| 4 | 6 | 48 | 100 | 111 | 128 | 206 |
| 4 | 7 | 99 | 128 | 141 | 146 | 174 |
| 4 | 8 | 77 | 140 | 161 | 179 | 250 |
| 4 | 9 | 10 | 122 | 170 | 198 | 216 |
| 5 | 1 | 5 | 20 | 30 | 61 | 99 |
| 5 | 2 | 10 | 40 | 49 | 84 | 148 |
| 5 | 3 | 10 | 51 | 88 | 103 | 130 |
| 5 | 4 | 14 | 78 | 103 | 122 | 202 |
| 5 | 5 | 48 | 99 | 105 | 119 | 152 |
| 5 | 6 | 70 | 120 | 125 | 143 | 223 |
| 5 | 7 | 101 | 120 | 150 | 177 | 313 |
| 5 | 8 | 68 | 118 | 150 | 192 | 295 |
| 5 | 9 | 79 | 155 | 181 | 246 | 359 |
| 6.3 | 1 | 19 | 40 | 66 | 96 | 139 |
| 6.3 | 2 | 20 | 57 | 77 | 100 | 160 |
| 6.3 | 3 | 50 | 79 | 107 | 120 | 248 |
| 6.3 | 4 | 50 | 93 | 117 | 146 | 231 |
| 6.3 | 5 | 57 | 115 | 120 | 138 | 201 |
| 6.3 | 6 | 76 | 119 | 134 | 172 | 309 |
| 6.3 | 7 | 80 | 145 | 150 | 187 | 297 |
| 6.3 | 8 | 101 | 164 | 179 | 197 | 273 |
| 6.3 | 9 | 105 | 172 | 196 | 247 | 350 |

Table C.8: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Lateral vibration, part 4/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 8 | 1 | 20 | 49 | 107 | 131 | 250 |
| 8 | 2 | 40 | 69 | 106 | 138 | 200 |
| 8 | 3 | 60 | 90 | 125 | 161 | 254 |
| 8 | 4 | 50 | 107 | 121 | 159 | 238 |
| 8 | 5 | 56 | 121 | 138 | 172 | 350 |
| 8 | 6 | 98 | 132 | 156 | 197 | 306 |
| 8 | 7 | 91 | 146 | 171 | 211 | 347 |
| 8 | 8 | 104 | 168 | 193 | 242 | 399 |
| 8 | 9 | 110 | 190 | 208 | 262 | 407 |
| 10 | 1 | 30 | 67 | 119 | 154 | 255 |
| 10 | 2 | 40 | 88 | 124 | 143 | 200 |
| 10 | 3 | 60 | 103 | 112 | 132 | 305 |
| 10 | 4 | 59 | 127 | 147 | 168 | 306 |
| 10 | 5 | 70 | 146 | 166 | 187 | 299 |
| 10 | 6 | 83 | 136 | 163 | 203 | 351 |
| 10 | 7 | 80 | 146 | 187 | 249 | 407 |
| 10 | 8 | 89 | 194 | 209 | 265 | 407 |
| 10 | 9 | 69 | 195 | 221 | 315 | 410 |
| 12.5 | 1 | 39 | 79 | 116 | 143 | 237 |
| 12.5 | 2 | 20 | 78 | 118 | 133 | 249 |
| 12.5 | 3 | 30 | 94 | 133 | 161 | 276 |
| 12.5 | 4 | 29 | 128 | 149 | 174 | 315 |
| 12.5 | 5 | 40 | 142 | 165 | 179 | 278 |
| 12.5 | 6 | 58 | 109 | 161 | 200 | 305 |
| 12.5 | 7 | 39 | 153 | 180 | 195 | 288 |
| 12.5 | 8 | 89 | 183 | 196 | 224 | 450 |
| 12.5 | 9 | 60 | 195 | 240 | 312 | 465 |
| 16 | 1 | 20 | 67 | 115 | 139 | 249 |
| 16 | 2 | 21 | 110 | 126 | 138 | 306 |
| 16 | 3 | 20 | 116 | 137 | 160 | 253 |
| 16 | 4 | 30 | 131 | 168 | 186 | 251 |
| 16 | 5 | 40 | 125 | 149 | 202 | 273 |
| 16 | 6 | 49 | 158 | 179 | 214 | 351 |
| 16 | 7 | 70 | 185 | 199 | 245 | 375 |
| 16 | 8 | 50 | 179 | 240 | 318 | 440 |
| 16 | 9 | 40 | 198 | 205 | 335 | 463 |

Table C.9: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Vertical vibration, part 1/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 0.5 | 1 | 1 | 2 | 10 | 11 | 40 |
| 0.5 | 2 | 5 | 7 | 11 | 23 | 72 |
| 0.5 | 3 | 1 | 8 | 36 | 52 | 71 |
| 0.5 | 4 | 1 | 18 | 50 | 82 | 161 |
| 0.5 | 5 | 5 | 32 | 50 | 100 | 159 |
| 0.5 | 6 | 10 | 29 | 89 | 150 | 213 |
| 0.5 | 7 | 15 | 74 | 105 | 165 | 211 |
| 0.5 | 8 | 19 | 118 | 165 | 204 | 263 |
| 0.5 | 9 | 38 | 126 | 161 | 264 | 368 |
| 0.63 | 1 | 1 | 5 | 10 | 32 | 51 |
| 0.63 | 2 | 5 | 9 | 25 | 34 | 139 |
| 0.63 | 3 | 1 | 11 | 40 | 61 | 111 |
| 0.63 | 4 | 10 | 32 | 61 | 87 | 127 |
| 0.63 | 5 | 10 | 50 | 80 | 116 | 170 |
| 0.63 | 6 | 21 | 94 | 115 | 157 | 207 |
| 0.63 | 7 | 21 | 82 | 135 | 167 | 290 |
| 0.63 | 8 | 38 | 125 | 155 | 186 | 321 |
| 0.63 | 9 | 29 | 160 | 194 | 219 | 477 |
| 0.8 | 1 | 1 | 8 | 10 | 26 | 74 |
| 0.8 | 2 | 5 | 10 | 15 | 32 | 72 |
| 0.8 | 3 | 5 | 18 | 51 | 60 | 160 |
| 0.8 | 4 | 10 | 37 | 59 | 128 | 193 |
| 0.8 | 5 | 20 | 56 | 64 | 110 | 158 |
| 0.8 | 6 | 28 | 63 | 109 | 154 | 214 |
| 0.8 | 7 | 57 | 112 | 132 | 190 | 264 |
| 0.8 | 8 | 48 | 128 | 172 | 208 | 362 |
| 0.8 | 9 | 96 | 143 | 185 | 288 | 418 |
| 1 | 1 | 5 | 10 | 26 | 48 | 80 |
| 1 | 2 | 5 | 20 | 41 | 53 | 103 |
| 1 | 3 | 15 | 31 | 70 | 107 | 160 |
| 1 | 4 | 14 | 42 | 78 | 119 | 159 |
| 1 | 5 | 40 | 79 | 117 | 135 | 210 |
| 1 | 6 | 60 | 118 | 127 | 152 | 213 |
| 1 | 7 | 96 | 147 | 174 | 205 | 322 |
| 1 | 8 | 106 | 147 | 207 | 255 | 465 |
| 1 | 9 | 49 | 183 | 221 | 336 | 510 |

Table C.10: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Vertical vibration, part 2/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 1.25 | 1 | 5 | 10 | 11 | 40 | 48 |
| 1.25 | 2 | 3 | 22 | 46 | 73 | 128 |
| 1.25 | 3 | 5 | 24 | 64 | 89 | 140 |
| 1.25 | 4 | 31 | 51 | 82 | 118 | 152 |
| 1.25 | 5 | 29 | 73 | 105 | 127 | 170 |
| 1.25 | 6 | 78 | 92 | 131 | 146 | 209 |
| 1.25 | 7 | 107 | 125 | 149 | 194 | 269 |
| 1.25 | 8 | 115 | 139 | 180 | 237 | 321 |
| 1.25 | 9 | 77 | 160 | 188 | 318 | 552 |
| 1.6 | 1 | 5 | 11 | 21 | 42 | 70 |
| 1.6 | 2 | 10 | 21 | 47 | 53 | 102 |
| 1.6 | 3 | 30 | 38 | 51 | 89 | 121 |
| 1.6 | 4 | 29 | 54 | 68 | 90 | 105 |
| 1.6 | 5 | 19 | 97 | 111 | 128 | 177 |
| 1.6 | 6 | 69 | 103 | 121 | 134 | 213 |
| 1.6 | 7 | 81 | 121 | 135 | 150 | 211 |
| 1.6 | 8 | 49 | 124 | 164 | 206 | 263 |
| 1.6 | 9 | 76 | 146 | 187 | 255 | 488 |
| 2 | 1 | 5 | 10 | 26 | 43 | 71 |
| 2 | 2 | 5 | 25 | 31 | 66 | 111 |
| 2 | 3 | 21 | 44 | 79 | 83 | 116 |
| 2 | 4 | 47 | 83 | 94 | 101 | 128 |
| 2 | 5 | 49 | 85 | 97 | 105 | 128 |
| 2 | 6 | 88 | 103 | 111 | 132 | 161 |
| 2 | 7 | 91 | 121 | 129 | 159 | 320 |
| 2 | 8 | 116 | 143 | 154 | 214 | 322 |
| 2 | 9 | 106 | 151 | 178 | 242 | 568 |
| 2.5 | 1 | 5 | 17 | 24 | 45 | 90 |
| 2.5 | 2 | 10 | 30 | 58 | 76 | 104 |
| 2.5 | 3 | 20 | 31 | 83 | 104 | 123 |
| 2.5 | 4 | 29 | 80 | 99 | 105 | 117 |
| 2.5 | 5 | 97 | 100 | 104 | 123 | 129 |
| 2.5 | 6 | 100 | 103 | 107 | 115 | 128 |
| 2.5 | 7 | 97 | 108 | 127 | 134 | 173 |
| 2.5 | 8 | 108 | 132 | 153 | 196 | 304 |
| 2.5 | 9 | 126 | 151 | 184 | 251 | 392 |

Table C.11: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Vertical vibration, part 3/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 3.15 | 1 | 9 | 17 | 21 | 53 | 97 |
| 3.15 | 2 | 21 | 31 | 49 | 73 | 101 |
| 3.15 | 3 | 29 | 74 | 94 | 107 | 110 |
| 3.15 | 4 | 31 | 85 | 100 | 106 | 123 |
| 3.15 | 5 | 82 | 115 | 124 | 130 | 220 |
| 3.15 | 6 | 85 | 105 | 120 | 138 | 320 |
| 3.15 | 7 | 114 | 127 | 147 | 167 | 319 |
| 3.15 | 8 | 126 | 143 | 157 | 211 | 421 |
| 3.15 | 9 | 106 | 150 | 190 | 242 | 399 |
| 4 | 1 | 5 | 22 | 31 | 53 | 111 |
| 4 | 2 | 29 | 47 | 61 | 85 | 119 |
| 4 | 3 | 31 | 84 | 94 | 111 | 158 |
| 4 | 4 | 53 | 91 | 118 | 126 | 146 |
| 4 | 5 | 82 | 114 | 145 | 159 | 211 |
| 4 | 6 | 85 | 126 | 179 | 191 | 229 |
| 4 | 7 | 90 | 141 | 158 | 208 | 371 |
| 4 | 8 | 114 | 153 | 185 | 222 | 438 |
| 4 | 9 | 158 | 173 | 193 | 275 | 631 |
| 5 | 1 | 48 | 64 | 85 | 86 | 129 |
| 5 | 2 | 62 | 85 | 111 | 124 | 160 |
| 5 | 3 | 76 | 94 | 126 | 134 | 173 |
| 5 | 4 | 51 | 120 | 136 | 166 | 338 |
| 5 | 5 | 111 | 134 | 150 | 188 | 321 |
| 5 | 6 | 127 | 145 | 155 | 212 | 468 |
| 5 | 7 | 126 | 172 | 186 | 209 | 541 |
| 5 | 8 | 127 | 159 | 208 | 251 | 601 |
| 5 | 9 | 172 | 211 | 265 | 320 | 549 |
| 6.3 | 1 | 10 | 82 | 86 | 118 | 143 |
| 6.3 | 2 | 58 | 119 | 129 | 148 | 213 |
| 6.3 | 3 | 84 | 124 | 142 | 224 | 267 |
| 6.3 | 4 | 118 | 126 | 149 | 186 | 323 |
| 6.3 | 5 | 51 | 125 | 156 | 193 | 360 |
| 6.3 | 6 | 116 | 156 | 168 | 233 | 479 |
| 6.3 | 7 | 126 | 178 | 201 | 339 | 557 |
| 6.3 | 8 | 117 | 193 | 215 | 303 | 596 |
| 6.3 | 9 | 159 | 201 | 252 | 330 | 628 |

Table C.12: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 4 with each test stimulus: Vertical vibration, part 4/4

| Freq. (Hz) | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| 8 | 1 | 20 | 82 | 126 | 136 | 199 |
| 8 | 2 | 30 | 84 | 114 | 135 | 214 |
| 8 | 3 | 41 | 89 | 127 | 142 | 175 |
| 8 | 4 | 110 | 139 | 154 | 183 | 301 |
| 8 | 5 | 71 | 128 | 150 | 222 | 375 |
| 8 | 6 | 69 | 172 | 192 | 247 | 411 |
| 8 | 7 | 111 | 157 | 196 | 261 | 569 |
| 8 | 8 | 129 | 177 | 226 | 313 | 581 |
| 8 | 9 | 159 | 202 | 249 | 365 | 644 |
| 10 | 1 | 21 | 70 | 88 | 107 | 143 |
| 10 | 2 | 53 | 84 | 111 | 138 | 189 |
| 10 | 3 | 41 | 102 | 130 | 144 | 214 |
| 10 | 4 | 41 | 128 | 152 | 166 | 203 |
| 10 | 5 | 91 | 126 | 160 | 213 | 451 |
| 10 | 6 | 92 | 146 | 176 | 211 | 432 |
| 10 | 7 | 107 | 156 | 209 | 258 | 430 |
| 10 | 8 | 150 | 197 | 211 | 294 | 537 |
| 10 | 9 | 160 | 207 | 276 | 322 | 648 |
| 12.5 | 1 | 30 | 80 | 121 | 129 | 166 |
| 12.5 | 2 | 65 | 86 | 127 | 150 | 178 |
| 12.5 | 3 | 40 | 119 | 129 | 145 | 214 |
| 12.5 | 4 | 53 | 122 | 141 | 195 | 254 |
| 12.5 | 5 | 41 | 152 | 177 | 209 | 382 |
| 12.5 | 6 | 40 | 141 | 181 | 246 | 316 |
| 12.5 | 7 | 124 | 168 | 215 | 259 | 448 |
| 12.5 | 8 | 118 | 206 | 247 | 344 | 743 |
| 12.5 | 9 | 160 | 240 | 276 | 371 | 745 |
| 16 | 1 | 40 | 90 | 120 | 147 | 211 |
| 16 | 2 | 10 | 89 | 130 | 155 | 222 |
| 16 | 3 | 21 | 119 | 141 | 164 | 263 |
| 16 | 4 | 92 | 147 | 179 | 202 | 296 |
| 16 | 5 | 64 | 155 | 168 | 206 | 324 |
| 16 | 6 | 52 | 176 | 198 | 256 | 530 |
| 16 | 7 | 92 | 184 | 224 | 312 | 623 |
| 16 | 8 | 92 | 197 | 261 | 326 | 629 |
| 16 | 9 | 131 | 211 | 257 | 400 | 1072 |

## C.2 Chapter 5

Table C.13: Summary (minimum, 25th percentile, median, 75th percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 5 with each reference/test pair (part 1/4)

| Ref. axis | Test axis | Mag. No. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| x | y | 1 | 10 | 45 | 50 | 70 | 100 |
| x | y | 2 | 30 | 45 | 55 | 75 | 90 |
| x | y | 3 | 30 | 50 | 70 | 80 | 100 |
| x | y | 4 | 30 | 73 | 95 | 100 | 100 |
| x | y | 5 | 50 | 75 | 90 | 103 | 150 |
| x | y | 6 | 60 | 81 | 100 | 110 | 120 |
| x | y | 7 | 90 | 100 | 100 | 120 | 170 |
| x | y | 8 | 80 | 98 | 110 | 133 | 200 |
| x | y | 9 | 70 | 108 | 125 | 130 | 180 |
| x | y | 10 | 120 | 130 | 140 | 165 | 250 |
| x | z | 1 | 10 | 38 | 65 | 80 | 100 |
| x | z | 2 | 30 | 60 | 78 | 100 | 120 |
| x | z | 3 | 20 | 60 | 70 | 93 | 100 |
| x | z | 4 | 30 | 80 | 105 | 113 | 170 |
| x | z | 5 | 50 | 100 | 120 | 120 | 150 |
| x | z | 6 | 50 | 100 | 110 | 133 | 200 |
| x | z | 7 | 100 | 118 | 120 | 133 | 200 |
| x | z | 8 | 110 | 124 | 140 | 193 | 200 |
| x | z | 9 | 120 | 150 | 195 | 200 | 320 |
| x | z | 10 | 130 | 150 | 175 | 263 | 300 |
| y | x | 1 | 10 | 30 | 50 | 63 | 80 |
| y | x | 2 | 20 | 60 | 70 | 100 | 125 |
| y | x | 3 | 50 | 78 | 85 | 100 | 110 |
| y | x | 4 | 60 | 90 | 100 | 100 | 130 |
| y | x | 5 | 70 | 88 | 100 | 113 | 150 |
| y | x | 6 | 90 | 100 | 100 | 133 | 180 |
| y | x | 7 | 90 | 100 | 125 | 143 | 170 |
| y | x | 8 | 90 | 100 | 120 | 143 | 180 |
| y | x | 9 | 100 | 120 | 150 | 176 | 220 |
| y | x | 10 | 140 | 150 | 155 | 185 | 300 |

Table C.14: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 5 with each reference/test pair (part 2/4)

| Ref. axis | Test axis | Mag. No. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| y | z | 1 | 20 | 50 | 75 | 89 | 120 |
| y | z | 2 | 20 | 48 | 73 | 100 | 110 |
| y | z | 3 | 50 | 78 | 93 | 105 | 130 |
| y | z | 4 | 50 | 80 | 100 | 133 | 150 |
| y | z | 5 | 80 | 90 | 115 | 153 | 170 |
| y | z | 6 | 85 | 118 | 130 | 153 | 200 |
| y | z | 7 | 110 | 120 | 128 | 158 | 350 |
| y | z | 8 | 110 | 134 | 150 | 160 | 200 |
| y | z | 9 | 140 | 168 | 190 | 200 | 300 |
| y | z | 10 | 120 | 180 | 200 | 220 | 350 |
| z | x | 1 | 10 | 20 | 40 | 53 | 90 |
| z | x | 2 | 10 | 40 | 50 | 53 | 90 |
| z | x | 3 | 20 | 40 | 60 | 76 | 90 |
| z | x | 4 | 10 | 38 | 80 | 80 | 100 |
| z | x | 5 | 20 | 65 | 85 | 100 | 100 |
| z | x | 6 | 30 | 78 | 95 | 105 | 120 |
| z | x | 7 | 30 | 95 | 100 | 133 | 140 |
| z | x | 8 | 70 | 99 | 123 | 133 | 200 |
| z | x | 9 | 50 | 120 | 133 | 163 | 250 |
| z | x | 10 | 90 | 128 | 150 | 153 | 180 |
| z | y | 1 | 20 | 20 | 45 | 66 | 80 |
| z | y | 2 | 20 | 28 | 60 | 68 | 130 |
| z | y | 3 | 20 | 48 | 65 | 90 | 120 |
| z | y | 4 | 35 | 60 | 80 | 80 | 110 |
| z | y | 5 | 30 | 55 | 75 | 105 | 120 |
| z | y | 6 | 30 | 65 | 90 | 93 | 120 |
| z | y | 7 | 60 | 80 | 90 | 113 | 170 |
| z | y | 8 | 50 | 94 | 105 | 120 | 200 |
| z | y | 9 | 25 | 98 | 100 | 133 | 220 |
| z | y | 10 | 105 | 110 | 125 | 135 | 250 |

Table C.15: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 5 with each reference/test pair (part 3/4)

| Ref. axis | Test axis | Mag. No. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| x | y | 1 | 20 | 46 | 55 | 70 | 80 |
| x | y | 2 | 10 | 35 | 75 | 83 | 100 |
| x | y | 3 | 15 | 50 | 73 | 80 | 100 |
| x | y | 4 | 50 | 78 | 80 | 100 | 120 |
| x | y | 5 | 70 | 80 | 90 | 100 | 110 |
| x | y | 6 | 60 | 88 | 100 | 100 | 110 |
| x | y | 7 | 65 | 100 | 105 | 113 | 150 |
| x | y | 8 | 75 | 100 | 110 | 120 | 250 |
| x | y | 9 | 105 | 120 | 135 | 150 | 230 |
| x | y | 10 | 100 | 120 | 140 | 180 | 220 |
| x | z | 1 | 10 | 50 | 80 | 100 | 120 |
| x | z | 2 | 20 | 69 | 80 | 85 | 110 |
| x | z | 3 | 30 | 80 | 100 | 103 | 130 |
| x | z | 4 | 60 | 80 | 100 | 115 | 200 |
| x | z | 5 | 70 | 100 | 110 | 133 | 150 |
| x | z | 6 | 90 | 110 | 120 | 135 | 300 |
| x | z | 7 | 120 | 124 | 130 | 150 | 160 |
| x | z | 8 | 110 | 138 | 145 | 200 | 250 |
| x | z | 9 | 120 | 145 | 175 | 250 | 275 |
| x | z | 10 | 120 | 173 | 205 | 278 | 300 |
| y | x | 1 | 20 | 38 | 50 | 60 | 80 |
| y | x | 2 | 10 | 45 | 70 | 89 | 100 |
| y | x | 3 | 30 | 50 | 80 | 100 | 110 |
| y | x | 4 | 30 | 81 | 95 | 100 | 160 |
| y | x | 5 | 50 | 100 | 100 | 110 | 140 |
| y | x | 6 | 100 | 110 | 120 | 120 | 175 |
| y | x | 7 | 90 | 100 | 115 | 125 | 180 |
| y | x | 8 | 100 | 120 | 145 | 170 | 200 |
| y | x | 9 | 100 | 128 | 135 | 163 | 250 |
| y | x | 10 | 140 | 150 | 180 | 213 | 370 |

Table C.16: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 5 with each reference/test pair (part 4/4)

| Ref. axis | Test axis | Mag. No. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| y | z | 1 | 30 | 68 | 78 | 80 | 90 |
| y | z | 2 | 10 | 50 | 65 | 93 | 110 |
| y | z | 3 | 60 | 80 | 100 | 100 | 140 |
| y | z | 4 | 80 | 94 | 105 | 110 | 150 |
| y | z | 5 | 100 | 108 | 115 | 145 | 200 |
| y | z | 6 | 60 | 120 | 130 | 155 | 225 |
| y | z | 7 | 100 | 130 | 150 | 185 | 200 |
| y | z | 8 | 130 | 160 | 190 | 200 | 300 |
| y | z | 9 | 140 | 173 | 200 | 220 | 250 |
| y | z | 10 | 140 | 179 | 200 | 223 | 350 |
| z | x | 1 | 15 | 28 | 50 | 63 | 80 |
| z | x | 2 | 20 | 39 | 50 | 70 | 80 |
| z | x | 3 | 20 | 30 | 55 | 73 | 110 |
| z | x | 4 | 20 | 55 | 73 | 83 | 90 |
| z | x | 5 | 30 | 69 | 80 | 81 | 110 |
| z | x | 6 | 20 | 78 | 100 | 103 | 120 |
| z | x | 7 | 50 | 88 | 100 | 113 | 140 |
| z | x | 8 | 50 | 108 | 120 | 133 | 180 |
| z | x | 9 | 80 | 118 | 125 | 160 | 170 |
| z | x | 10 | 100 | 145 | 160 | 178 | 200 |
| z | y | 1 | 10 | 30 | 40 | 63 | 100 |
| z | y | 2 | 15 | 35 | 55 | 65 | 90 |
| z | y | 3 | 20 | 44 | 63 | 83 | 110 |
| z | y | 4 | 20 | 63 | 75 | 90 | 100 |
| z | y | 5 | 20 | 48 | 75 | 80 | 100 |
| z | y | 6 | 70 | 88 | 95 | 103 | 120 |
| z | y | 7 | 40 | 80 | 95 | 100 | 130 |
| z | y | 8 | 40 | 88 | 105 | 120 | 250 |
| z | y | 9 | 80 | 90 | 105 | 120 | 150 |
| z | y | 10 | 100 | 119 | 128 | 140 | 200 |

## C.3 Chapter 6

Table C.17: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Fore-and-aft vibration, no support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Free | 0.5 | 1 | 10 | 14 | 44 | 53 | 92 |
| Free | 0.5 | 2 | 18 | 51 | 131 | 238 | 415 |
| Free | 0.5 | 3 | 82 | 132 | 143 | 257 | 852 |
| Free | 0.5 | 4 | 186 | 210 | 257 | 494 | 1218 |
| Free | 0.5 | 5 | 273 | 354 | 636 | 925 | 1724 |
| Free | 1 | 1 | 3 | 18 | 34 | 65 | 73 |
| Free | 1 | 2 | 26 | 42 | 76 | 101 | 129 |
| Free | 1 | 3 | 50 | 79 | 132 | 188 | 387 |
| Free | 1 | 4 | 51 | 137 | 215 | 310 | 769 |
| Free | 1 | 5 | 53 | 214 | 339 | 407 | 1022 |
| Free | 2 | 1 | 3 | 15 | 21 | 56 | 114 |
| Free | 2 | 2 | 5 | 39 | 51 | 99 | 268 |
| Free | 2 | 3 | 15 | 51 | 99 | 131 | 336 |
| Free | 2 | 4 | 15 | 97 | 134 | 221 | 389 |
| Free | 2 | 5 | 31 | 129 | 234 | 305 | 510 |
| Free | 4 | 1 | 0 | 8 | 11 | 31 | 86 |
| Free | 4 | 2 | 2 | 19 | 42 | 63 | 93 |
| Free | 4 | 3 | 2 | 47 | 78 | 129 | 383 |
| Free | 4 | 4 | 7 | 67 | 131 | 162 | 472 |
| Free | 4 | 5 | 37 | 85 | 178 | 269 | 718 |
| Free | 8 | 1 | 1 | 6 | 13 | 35 | 79 |
| Free | 8 | 2 | 2 | 18 | 30 | 44 | 121 |
| Free | 8 | 3 | 15 | 35 | 50 | 99 | 144 |
| Free | 8 | 4 | 24 | 58 | 66 | 127 | 194 |
| Free | 8 | 5 | 25 | 111 | 120 | 154 | 295 |
| Free | 16 | 1 | 1 | 4 | 8 | 18 | 35 |
| Free | 16 | 2 | 6 | 11 | 17 | 33 | 62 |
| Free | 16 | 3 | 8 | 17 | 33 | 61 | 82 |
| Free | 16 | 4 | 11 | 28 | 56 | 68 | 149 |
| Free | 16 | 5 | 30 | 47 | 95 | 122 | 237 |

Table C.18: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Fore-and-aft vibration, bar)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Bar | 0.5 | 1 | 4 | 16 | 36 | 84 | 522 |
| Bar | 0.5 | 2 | 18 | 54 | 71 | 189 | 299 |
| Bar | 0.5 | 3 | 17 | 111 | 245 | 333 | 419 |
| Bar | 0.5 | 4 | 35 | 298 | 439 | 506 | 668 |
| Bar | 0.5 | 5 | 224 | 292 | 474 | 610 | 836 |
| Bar | 1 | 1 | 2 | 12 | 27 | 44 | 66 |
| Bar | 1 | 2 | 2 | 24 | 40 | 62 | 213 |
| Bar | 1 | 3 | 5 | 65 | 102 | 176 | 523 |
| Bar | 1 | 4 | 9 | 163 | 223 | 394 | 613 |
| Bar | 1 | 5 | 37 | 289 | 335 | 467 | 705 |
| Bar | 2 | 1 | 2 | 11 | 24 | 34 | 97 |
| Bar | 2 | 2 | 6 | 22 | 39 | 68 | 85 |
| Bar | 2 | 3 | 13 | 36 | 67 | 83 | 121 |
| Bar | 2 | 4 | 14 | 76 | 94 | 125 | 164 |
| Bar | 2 | 5 | 35 | 115 | 147 | 191 | 216 |
| Bar | 4 | 1 | 1 | 12 | 40 | 42 | 81 |
| Bar | 4 | 2 | 9 | 17 | 56 | 89 | 208 |
| Bar | 4 | 3 | 22 | 38 | 116 | 208 | 227 |
| Bar | 4 | 4 | 38 | 51 | 191 | 256 | 354 |
| Bar | 4 | 5 | 39 | 62 | 303 | 359 | 621 |
| Bar | 8 | 1 | 2 | 8 | 11 | 24 | 273 |
| Bar | 8 | 2 | 8 | 13 | 22 | 57 | 119 |
| Bar | 8 | 3 | 18 | 22 | 30 | 100 | 331 |
| Bar | 8 | 4 | 32 | 41 | 65 | 101 | 416 |
| Bar | 8 | 5 | 38 | 67 | 95 | 163 | 655 |
| Bar | 16 | 1 | 5 | 7 | 14 | 22 | 74 |
| Bar | 16 | 2 | 4 | 16 | 24 | 31 | 81 |
| Bar | 16 | 3 | 7 | 19 | 30 | 69 | 101 |
| Bar | 16 | 4 | 9 | 24 | 44 | 73 | 176 |
| Bar | 16 | 5 | 13 | 39 | 73 | 128 | 303 |

Table C.19: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Fore-and-aft vibration, shoulder support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Shoulder | 0.5 | 1 | 19 | 24 | 46 | 57 | 81 |
| Shoulder | 0.5 | 2 | 23 | 65 | 92 | 139 | 241 |
| Shoulder | 0.5 | 3 | 46 | 115 | 229 | 321 | 817 |
| Shoulder | 0.5 | 4 | 124 | 307 | 404 | 627 | 1612 |
| Shoulder | 0.5 | 5 | 351 | 497 | 578 | 1102 | 2467 |
| Shoulder | 1 | 1 | 6 | 20 | 23 | 63 | 199 |
| Shoulder | 1 | 2 | 12 | 60 | 89 | 137 | 159 |
| Shoulder | 1 | 3 | 54 | 64 | 146 | 249 | 405 |
| Shoulder | 1 | 4 | 65 | 108 | 219 | 343 | 601 |
| Shoulder | 1 | 5 | 94 | 224 | 359 | 499 | 1025 |
| Shoulder | 2 | 1 | 5 | 31 | 46 | 71 | 115 |
| Shoulder | 2 | 2 | 14 | 61 | 99 | 119 | 253 |
| Shoulder | 2 | 3 | 47 | 82 | 131 | 221 | 361 |
| Shoulder | 2 | 4 | 51 | 111 | 187 | 368 | 448 |
| Shoulder | 2 | 5 | 69 | 184 | 257 | 419 | 658 |
| Shoulder | 4 | 1 | 4 | 13 | 20 | 24 | 52 |
| Shoulder | 4 | 2 | 8 | 16 | 34 | 62 | 83 |
| Shoulder | 4 | 3 | 31 | 40 | 54 | 90 | 637 |
| Shoulder | 4 | 4 | 34 | 64 | 143 | 148 | 809 |
| Shoulder | 4 | 5 | 65 | 122 | 137 | 174 | 1033 |
| Shoulder | 8 | 1 | 3 | 14 | 23 | 34 | 99 |
| Shoulder | 8 | 2 | 3 | 24 | 34 | 60 | 157 |
| Shoulder | 8 | 3 | 6 | 34 | 58 | 121 | 195 |
| Shoulder | 8 | 4 | 12 | 74 | 106 | 163 | 506 |
| Shoulder | 8 | 5 | 14 | 117 | 157 | 191 | 488 |
| Shoulder | 16 | 1 | 1 | 4 | 11 | 19 | 45 |
| Shoulder | 16 | 2 | 3 | 12 | 19 | 34 | 66 |
| Shoulder | 16 | 3 | 4 | 19 | 29 | 53 | 102 |
| Shoulder | 16 | 4 | 11 | 23 | 50 | 79 | 125 |
| Shoulder | 16 | 5 | 19 | 51 | 86 | 123 | 433 |

Table C.20: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Fore-and-aft vibration, back support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Back | 0.5 | 1 | 9 | 26 | 51 | 120 | 199 |
| Back | 0.5 | 2 | 15 | 70 | 118 | 161 | 465 |
| Back | 0.5 | 3 | 65 | 105 | 162 | 378 | 758 |
| Back | 0.5 | 4 | 101 | 177 | 400 | 527 | 1047 |
| Back | 0.5 | 5 | 167 | 324 | 475 | 678 | 1187 |
| Back | 1 | 1 | 6 | 15 | 25 | 45 | 139 |
| Back | 1 | 2 | 18 | 27 | 37 | 107 | 342 |
| Back | 1 | 3 | 22 | 53 | 111 | 213 | 754 |
| Back | 1 | 4 | 51 | 90 | 266 | 376 | 1034 |
| Back | 1 | 5 | 71 | 115 | 374 | 661 | 2308 |
| Back | 2 | 1 | 22 | 41 | 73 | 91 | 147 |
| Back | 2 | 2 | 21 | 100 | 130 | 144 | 272 |
| Back | 2 | 3 | 82 | 138 | 153 | 232 | 329 |
| Back | 2 | 4 | 117 | 187 | 247 | 400 | 547 |
| Back | 2 | 5 | 206 | 269 | 483 | 697 | 1171 |
| Back | 4 | 1 | 14 | 50 | 74 | 139 | 562 |
| Back | 4 | 2 | 22 | 48 | 104 | 207 | 754 |
| Back | 4 | 3 | 25 | 74 | 190 | 396 | 941 |
| Back | 4 | 4 | 34 | 202 | 269 | 407 | 1552 |
| Back | 4 | 5 | 59 | 194 | 260 | 456 | 3275 |
| Back | 8 | 1 | 6 | 18 | 64 | 97 | 404 |
| Back | 8 | 2 | 13 | 56 | 74 | 108 | 254 |
| Back | 8 | 3 | 30 | 51 | 81 | 172 | 465 |
| Back | 8 | 4 | 48 | 94 | 148 | 273 | 502 |
| Back | 8 | 5 | 41 | 103 | 126 | 360 | 686 |
| Back | 16 | 1 | 8 | 30 | 60 | 83 | 318 |
| Back | 16 | 2 | 29 | 51 | 61 | 99 | 330 |
| Back | 16 | 3 | 22 | 69 | 96 | 123 | 501 |
| Back | 16 | 4 | 40 | 87 | 124 | 164 | 644 |
| Back | 16 | 5 | 71 | 142 | 194 | 236 | 1494 |

Table C.21: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Lateral vibration, no support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Free | 0.5 | 1 | 10 | 35 | 41 | 57 | 224 |
| Free | 0.5 | 2 | 20 | 41 | 76 | 100 | 152 |
| Free | 0.5 | 3 | 55 | 91 | 137 | 183 | 249 |
| Free | 0.5 | 4 | 117 | 220 | 381 | 492 | 618 |
| Free | 0.5 | 5 | 269 | 411 | 509 | 629 | 932 |
| Free | 1 | 1 | 11 | 15 | 30 | 45 | 121 |
| Free | 1 | 2 | 20 | 39 | 60 | 79 | 681 |
| Free | 1 | 3 | 25 | 78 | 138 | 178 | 622 |
| Free | 1 | 4 | 63 | 182 | 268 | 296 | 418 |
| Free | 1 | 5 | 60 | 263 | 354 | 415 | 1175 |
| Free | 2 | 1 | 2 | 7 | 22 | 33 | 70 |
| Free | 2 | 2 | 3 | 17 | 55 | 78 | 160 |
| Free | 2 | 3 | 8 | 42 | 96 | 103 | 204 |
| Free | 2 | 4 | 14 | 56 | 105 | 120 | 232 |
| Free | 2 | 5 | 19 | 90 | 119 | 207 | 394 |
| Free | 4 | 1 | 0 | 8 | 10 | 18 | 20 |
| Free | 4 | 2 | 5 | 16 | 23 | 38 | 138 |
| Free | 4 | 3 | 2 | 19 | 67 | 129 | 206 |
| Free | 4 | 4 | 5 | 63 | 126 | 176 | 273 |
| Free | 4 | 5 | 15 | 85 | 154 | 255 | 310 |
| Free | 8 | 1 | 3 | 5 | 7 | 12 | 105 |
| Free | 8 | 2 | 8 | 12 | 19 | 25 | 71 |
| Free | 8 | 3 | 13 | 22 | 44 | 67 | 106 |
| Free | 8 | 4 | 20 | 37 | 72 | 103 | 249 |
| Free | 8 | 5 | 35 | 77 | 112 | 153 | 351 |
| Free | 16 | 1 | 3 | 5 | 13 | 17 | 78 |
| Free | 16 | 2 | 5 | 9 | 20 | 31 | 125 |
| Free | 16 | 3 | 20 | 24 | 38 | 54 | 130 |
| Free | 16 | 4 | 10 | 32 | 49 | 79 | 192 |
| Free | 16 | 5 | 33 | 67 | 93 | 140 | 331 |

Table C.22: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Lateral vibration, bar)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Bar | 0.5 | 1 | 13 | 32 | 56 | 143 | 261 |
| Bar | 0.5 | 2 | 22 | 91 | 141 | 172 | 483 |
| Bar | 0.5 | 3 | 24 | 162 | 270 | 388 | 586 |
| Bar | 0.5 | 4 | 65 | 230 | 400 | 621 | 827 |
| Bar | 0.5 | 5 | 144 | 344 | 494 | 691 | 1384 |
| Bar | 1 | 1 | 6 | 39 | 55 | 74 | 96 |
| Bar | 1 | 2 | 6 | 29 | 116 | 131 | 484 |
| Bar | 1 | 3 | 9 | 122 | 172 | 208 | 489 |
| Bar | 1 | 4 | 31 | 144 | 263 | 514 | 662 |
| Bar | 1 | 5 | 74 | 191 | 331 | 543 | 1127 |
| Bar | 2 | 1 | 1 | 8 | 14 | 40 | 113 |
| Bar | 2 | 2 | 7 | 21 | 30 | 82 | 205 |
| Bar | 2 | 3 | 14 | 40 | 66 | 141 | 282 |
| Bar | 2 | 4 | 13 | 48 | 103 | 208 | 338 |
| Bar | 2 | 5 | 27 | 62 | 121 | 253 | 850 |
| Bar | 4 | 1 | 2 | 6 | 9 | 33 | 54 |
| Bar | 4 | 2 | 4 | 12 | 23 | 51 | 94 |
| Bar | 4 | 3 | 12 | 17 | 60 | 137 | 300 |
| Bar | 4 | 4 | 15 | 36 | 134 | 162 | 295 |
| Bar | 4 | 5 | 26 | 68 | 137 | 207 | 304 |
| Bar | 8 | 1 | 3 | 6 | 10 | 19 | 28 |
| Bar | 8 | 2 | 3 | 9 | 12 | 32 | 121 |
| Bar | 8 | 3 | 8 | 28 | 40 | 67 | 190 |
| Bar | 8 | 4 | 15 | 47 | 77 | 90 | 222 |
| Bar | 8 | 5 | 19 | 78 | 102 | 116 | 244 |
| Bar | 16 | 1 | 7 | 9 | 12 | 19 | 72 |
| Bar | 16 | 2 | 15 | 18 | 29 | 47 | 107 |
| Bar | 16 | 3 | 16 | 36 | 40 | 57 | 120 |
| Bar | 16 | 4 | 19 | 51 | 60 | 78 | 179 |
| Bar | 16 | 5 | 35 | 95 | 102 | 148 | 267 |

Table C.23: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Lateral vibration, shoulder support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Shoulder | 0.5 | 1 | 21 | 31 | 55 | 88 | 95 |
| Shoulder | 0.5 | 2 | 28 | 41 | 71 | 127 | 310 |
| Shoulder | 0.5 | 3 | 43 | 84 | 163 | 213 | 336 |
| Shoulder | 0.5 | 4 | 81 | 183 | 222 | 290 | 880 |
| Shoulder | 0.5 | 5 | 144 | 281 | 406 | 461 | 1332 |
| Shoulder | 1 | 1 | 7 | 38 | 47 | 62 | 173 |
| Shoulder | 1 | 2 | 37 | 56 | 111 | 138 | 343 |
| Shoulder | 1 | 3 | 44 | 118 | 194 | 250 | 876 |
| Shoulder | 1 | 4 | 111 | 249 | 299 | 427 | 2152 |
| Shoulder | 1 | 5 | 149 | 350 | 472 | 577 | 2785 |
| Shoulder | 2 | 1 | 8 | 21 | 31 | 67 | 280 |
| Shoulder | 2 | 2 | 31 | 36 | 95 | 140 | 350 |
| Shoulder | 2 | 3 | 28 | 76 | 117 | 178 | 585 |
| Shoulder | 2 | 4 | 45 | 105 | 223 | 328 | 1049 |
| Shoulder | 2 | 5 | 54 | 112 | 232 | 441 | 13492 |
| Shoulder | 4 | 1 | 8 | 19 | 63 | 81 | 137 |
| Shoulder | 4 | 2 | 16 | 43 | 108 | 131 | 214 |
| Shoulder | 4 | 3 | 21 | 56 | 134 | 221 | 475 |
| Shoulder | 4 | 4 | 31 | 172 | 252 | 433 | 492 |
| Shoulder | 4 | 5 | 40 | 146 | 383 | 507 | 963 |
| Shoulder | 8 | 1 | 7 | 22 | 43 | 63 | 123 |
| Shoulder | 8 | 2 | 11 | 45 | 110 | 121 | 162 |
| Shoulder | 8 | 3 | 32 | 70 | 132 | 196 | 235 |
| Shoulder | 8 | 4 | 37 | 83 | 134 | 261 | 722 |
| Shoulder | 8 | 5 | 42 | 122 | 235 | 331 | 917 |
| Shoulder | 16 | 1 | 3 | 11 | 25 | 58 | 102 |
| Shoulder | 16 | 2 | 9 | 22 | 49 | 107 | 243 |
| Shoulder | 16 | 3 | 14 | 40 | 59 | 96 | 174 |
| Shoulder | 16 | 4 | 16 | 60 | 99 | 147 | 576 |
| Shoulder | 16 | 5 | 24 | 109 | 181 | 216 | 481 |

Table C.24: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 6 with each test stimulus (Lateral vibration, back support)

| Support | Freq. (Hz) | Mag no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| Back | 0.5 | 1 | 21 | 46 | 72 | 96 | 226 |
| Back | 0.5 | 2 | 20 | 70 | 105 | 189 | 636 |
| Back | 0.5 | 3 | 16 | 89 | 160 | 358 | 654 |
| Back | 0.5 | 4 | 82 | 190 | 325 | 725 | 1741 |
| Back | 0.5 | 5 | 131 | 315 | 492 | 1136 | 3277 |
| Back | 1 | 1 | 7 | 15 | 18 | 74 | 158 |
| Back | 1 | 2 | 15 | 42 | 144 | 188 | 220 |
| Back | 1 | 3 | 23 | 89 | 128 | 202 | 648 |
| Back | 1 | 4 | 88 | 129 | 300 | 419 | 677 |
| Back | 1 | 5 | 102 | 146 | 328 | 566 | 1565 |
| Back | 2 | 1 | 21 | 47 | 69 | 111 | 180 |
| Back | 2 | 2 | 42 | 66 | 105 | 179 | 351 |
| Back | 2 | 3 | 45 | 116 | 141 | 253 | 399 |
| Back | 2 | 4 | 51 | 134 | 239 | 370 | 575 |
| Back | 2 | 5 | 62 | 177 | 248 | 607 | 919 |
| Back | 4 | 1 | 6 | 16 | 24 | 58 | 215 |
| Back | 4 | 2 | 7 | 22 | 42 | 121 | 208 |
| Back | 4 | 3 | 15 | 55 | 117 | 157 | 315 |
| Back | 4 | 4 | 31 | 61 | 161 | 237 | 362 |
| Back | 4 | 5 | 41 | 68 | 184 | 304 | 417 |
| Back | 8 | 1 | 2 | 5 | 13 | 28 | 80 |
| Back | 8 | 2 | 3 | 7 | 28 | 61 | 82 |
| Back | 8 | 3 | 6 | 28 | 47 | 80 | 169 |
| Back | 8 | 4 | 9 | 38 | 98 | 144 | 209 |
| Back | 8 | 5 | 11 | 66 | 163 | 254 | 374 |
| Back | 16 | 1 | 2 | 12 | 14 | 20 | 97 |
| Back | 16 | 2 | 6 | 10 | 18 | 29 | 140 |
| Back | 16 | 3 | 8 | 26 | 33 | 53 | 190 |
| Back | 16 | 4 | 20 | 38 | 46 | 72 | 193 |
| Back | 16 | 5 | 30 | 71 | 90 | 107 | 396 |

## C.4 Chapter 7

Table C.25: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Fore-and-aft vibration, part 1/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 1 | A | 1 | 21 | 58 | 58 | 90 | 100 |
| 1 | A | 2 | 30 | 80 | 80 | 100 | 150 |
| 1 | A | 3 | 20 | 70 | 70 | 100 | 120 |
| 1 | A | 4 | 70 | 90 | 90 | 100 | 140 |
| 1 | A | 5 | 70 | 88 | 88 | 110 | 130 |
| 1 | A | 6 | 80 | 100 | 100 | 121 | 220 |
| 1 | A | 7 | 90 | 100 | 100 | 153 | 200 |
| 1 | A | 8 | 90 | 108 | 108 | 163 | 210 |
| 1 | A | 9 | 75 | 110 | 110 | 143 | 300 |
| 1 | B | 1 | 40 | 68 | 68 | 93 | 130 |
| 1 | B | 2 | 27 | 80 | 80 | 110 | 120 |
| 1 | B | 3 | 60 | 80 | 80 | 120 | 150 |
| 1 | B | 4 | 70 | 94 | 94 | 121 | 205 |
| 1 | B | 5 | 70 | 108 | 108 | 140 | 400 |
| 1 | B | 6 | 60 | 100 | 100 | 150 | 180 |
| 1 | B | 7 | 80 | 120 | 120 | 163 | 200 |
| 1 | B | 8 | 72 | 128 | 128 | 180 | 250 |
| 1 | B | 9 | 110 | 150 | 150 | 200 | 444 |
| 1 | C | 1 | 40 | 58 | 58 | 100 | 200 |
| 1 | C | 2 | 50 | 70 | 70 | 103 | 130 |
| 1 | C | 3 | 70 | 80 | 80 | 123 | 200 |
| 1 | C | 4 | 50 | 80 | 80 | 125 | 200 |
| 1 | C | 5 | 75 | 100 | 100 | 153 | 300 |
| 1 | C | 6 | 90 | 108 | 108 | 153 | 400 |
| 1 | C | 7 | 80 | 118 | 118 | 150 | 300 |
| 1 | C | 8 | 100 | 130 | 130 | 200 | 400 |
| 1 | C | 9 | 90 | 120 | 120 | 200 | 300 |
| 1 | D | 1 | 10 | 70 | 70 | 113 | 200 |
| 1 | D | 2 | 40 | 70 | 70 | 120 | 140 |
| 1 | D | 3 | 50 | 88 | 88 | 120 | 150 |
| 1 | D | 4 | 40 | 90 | 90 | 130 | 180 |

Table C.26: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Fore-and-aft vibration, part 2/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 1 | D | 5 | 70 | 106 | 106 | 135 | 180 |
| 1 | D | 6 | 80 | 108 | 108 | 150 | 210 |
| 1 | D | 7 | 61 | 120 | 120 | 155 | 250 |
| 1 | D | 8 | 90 | 128 | 128 | 192 | 300 |
| 1 | D | 9 | 120 | 158 | 158 | 200 | 350 |
| 1 | E | 1 | 36 | 70 | 70 | 100 | 150 |
| 1 | E | 2 | 55 | 88 | 88 | 103 | 160 |
| 1 | E | 3 | 35 | 58 | 58 | 110 | 180 |
| 1 | E | 4 | 72 | 80 | 80 | 121 | 180 |
| 1 | E | 5 | 44 | 94 | 94 | 150 | 250 |
| 1 | E | 6 | 80 | 118 | 118 | 155 | 300 |
| 1 | E | 7 | 76 | 110 | 110 | 165 | 400 |
| 1 | E | 8 | 100 | 120 | 120 | 170 | 400 |
| 1 | E | 9 | 120 | 140 | 140 | 200 | 376 |
| 1 | F | 1 | 1 | 68 | 68 | 110 | 150 |
| 1 | F | 2 | 50 | 79 | 79 | 113 | 269 |
| 1 | F | 3 | 50 | 80 | 80 | 120 | 320 |
| 1 | F | 4 | 50 | 95 | 95 | 135 | 234 |
| 1 | F | 5 | 50 | 110 | 110 | 150 | 255 |
| 1 | F | 6 | 90 | 124 | 124 | 196 | 200 |
| 1 | F | 7 | 85 | 140 | 140 | 200 | 300 |
| 1 | F | 8 | 90 | 140 | 140 | 183 | 255 |
| 1 | F | 9 | 120 | 148 | 148 | 213 | 580 |
| 1 | G | 1 | 30 | 68 | 68 | 93 | 130 |
| 1 | G | 2 | 30 | 58 | 58 | 113 | 193 |
| 1 | G | 3 | 60 | 80 | 80 | 113 | 180 |
| 1 | G | 4 | 50 | 100 | 100 | 173 | 200 |
| 1 | G | 5 | 53 | 99 | 99 | 155 | 300 |
| 1 | G | 6 | 70 | 118 | 118 | 176 | 200 |
| 1 | G | 7 | 110 | 148 | 148 | 196 | 400 |
| 1 | G | 8 | 120 | 148 | 148 | 203 | 300 |
| 1 | G | 9 | 120 | 148 | 148 | 228 | 580 |

Table C.27: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Fore-and-aft vibration, part 3/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | A | 1 | 10 | 60 | 60 | 80 | 110 |
| 8 | A | 2 | 50 | 79 | 79 | 100 | 100 |
| 8 | A | 3 | 40 | 94 | 94 | 100 | 110 |
| 8 | A | 4 | 60 | 80 | 80 | 100 | 110 |
| 8 | A | 5 | 60 | 90 | 90 | 100 | 120 |
| 8 | A | 6 | 40 | 100 | 100 | 105 | 150 |
| 8 | A | 7 | 100 | 100 | 100 | 110 | 140 |
| 8 | A | 8 | 85 | 100 | 100 | 123 | 200 |
| 8 | A | 9 | 90 | 100 | 100 | 130 | 200 |
| 8 | B | 1 | 20 | 65 | 65 | 100 | 120 |
| 8 | B | 2 | 40 | 80 | 80 | 100 | 130 |
| 8 | B | 3 | 30 | 80 | 80 | 103 | 120 |
| 8 | B | 4 | 60 | 98 | 98 | 120 | 141 |
| 8 | B | 5 | 70 | 100 | 100 | 111 | 179 |
| 8 | B | 6 | 35 | 100 | 100 | 120 | 218 |
| 8 | B | 7 | 90 | 110 | 110 | 140 | 220 |
| 8 | B | 8 | 80 | 118 | 118 | 153 | 300 |
| 8 | B | 9 | 110 | 128 | 128 | 150 | 275 |
| 8 | C | 1 | 40 | 74 | 74 | 100 | 110 |
| 8 | C | 2 | 20 | 58 | 58 | 103 | 130 |
| 8 | C | 3 | 50 | 80 | 80 | 113 | 150 |
| 8 | C | 4 | 50 | 80 | 80 | 131 | 150 |
| 8 | C | 5 | 65 | 90 | 90 | 120 | 150 |
| 8 | C | 6 | 50 | 108 | 108 | 140 | 250 |
| 8 | C | 7 | 95 | 114 | 114 | 123 | 160 |
| 8 | C | 8 | 70 | 114 | 114 | 150 | 200 |
| 8 | C | 9 | 100 | 111 | 111 | 140 | 200 |
| 8 | D | 1 | 20 | 50 | 50 | 100 | 146 |
| 8 | D | 2 | 25 | 90 | 90 | 110 | 150 |
| 8 | D | 3 | 40 | 80 | 80 | 101 | 400 |
| 8 | D | 4 | 70 | 88 | 88 | 120 | 200 |
| 8 | D | 5 | 80 | 100 | 100 | 120 | 202 |

Table C.28: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Fore-and-aft vibration, part 4/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | D | 6 | 90 | 110 | 110 | 126 | 140 |
| 8 | D | 7 | 70 | 118 | 118 | 150 | 400 |
| 8 | D | 8 | 75 | 120 | 120 | 135 | 227 |
| 8 | D | 9 | 100 | 120 | 120 | 153 | 203 |
| 8 | E | 1 | 50 | 68 | 68 | 101 | 150 |
| 8 | E | 2 | 20 | 74 | 74 | 110 | 150 |
| 8 | E | 3 | 40 | 79 | 79 | 103 | 120 |
| 8 | E | 4 | 20 | 90 | 90 | 121 | 190 |
| 8 | E | 5 | 70 | 89 | 89 | 130 | 160 |
| 8 | E | 6 | 70 | 108 | 108 | 150 | 200 |
| 8 | E | 7 | 80 | 110 | 110 | 143 | 216 |
| 8 | E | 8 | 80 | 114 | 114 | 155 | 217 |
| 8 | E | 9 | 110 | 129 | 129 | 160 | 220 |
| 8 | F | 1 | 35 | 60 | 60 | 90 | 157 |
| 8 | F | 2 | 15 | 58 | 58 | 90 | 150 |
| 8 | F | 3 | 50 | 80 | 80 | 113 | 165 |
| 8 | F | 4 | 50 | 89 | 89 | 121 | 183 |
| 8 | F | 5 | 50 | 100 | 100 | 129 | 200 |
| 8 | F | 6 | 50 | 99 | 99 | 123 | 197 |
| 8 | F | 7 | 70 | 110 | 110 | 150 | 300 |
| 8 | F | 8 | 80 | 120 | 120 | 143 | 210 |
| 8 | F | 9 | 75 | 130 | 130 | 163 | 300 |
| 8 | G | 1 | 20 | 74 | 74 | 113 | 200 |
| 8 | G | 2 | 20 | 70 | 70 | 113 | 215 |
| 8 | G | 3 | 50 | 84 | 84 | 120 | 150 |
| 8 | G | 4 | 50 | 104 | 104 | 126 | 212 |
| 8 | G | 5 | 70 | 100 | 100 | 130 | 150 |
| 8 | G | 6 | 70 | 108 | 108 | 150 | 184 |
| 8 | G | 7 | 80 | 119 | 119 | 150 | 237 |
| 8 | G | 8 | 60 | 119 | 119 | 150 | 305 |
| 8 | G | 9 | 120 | 130 | 130 | 159 | 200 |

Table C.29: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Lateral vibration, part 1/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 1 | A | 1 | 30 | 58.75 | 58.75 | 100 | 110 |
| 1 | A | 2 | 20 | 67.5 | 67.5 | 100 | 120 |
| 1 | A | 3 | 50 | 80 | 80 | 100 | 110 |
| 1 | A | 4 | 50 | 87.5 | 87.5 | 110 | 150 |
| 1 | A | 5 | 50 | 80 | 80 | 100 | 150 |
| 1 | A | 6 | 50 | 100 | 100 | 120 | 161 |
| 1 | A | 7 | 100 | 110 | 110 | 132.5 | 150 |
| 1 | A | 8 | 100 | 103.75 | 103.75 | 132.5 | 200 |
| 1 | A | 9 | 90 | 120 | 120 | 150 | 201 |
| 1 | B | 1 | 25 | 77.5 | 77.5 | 100 | 130 |
| 1 | B | 2 | 25 | 80 | 80 | 112.5 | 150 |
| 1 | B | 3 | 50 | 87.5 | 87.5 | 120.25 | 200 |
| 1 | B | 4 | 50 | 90 | 90 | 120 | 250 |
| 1 | B | 5 | 80 | 97.5 | 97.5 | 130 | 200 |
| 1 | B | 6 | 75 | 100 | 100 | 142.5 | 200 |
| 1 | B | 7 | 60 | 120 | 120 | 161.75 | 200 |
| 1 | B | 8 | 100 | 123.75 | 123.75 | 200 | 300 |
| 1 | B | 9 | 100 | 146.25 | 146.25 | 185 | 300 |
| 1 | C | 1 | 30 | 50 | 50 | 100 | 105 |
| 1 | C | 2 | 50 | 70 | 70 | 100 | 120 |
| 1 | C | 3 | 25 | 90 | 90 | 110 | 150 |
| 1 | C | 4 | 40 | 87.5 | 87.5 | 110 | 120 |
| 1 | C | 5 | 50 | 78.75 | 78.75 | 117 | 250 |
| 1 | C | 6 | 80 | 100 | 100 | 135 | 200 |
| 1 | C | 7 | 80 | 110 | 110 | 150 | 205 |
| 1 | C | 8 | 100 | 120 | 120 | 171.25 | 400 |
| 1 | C | 9 | 100 | 130 | 130 | 200 | 357 |
| 1 | D | 1 | 5 | 50 | 50 | 86.25 | 120 |
| 1 | D | 2 | 50 | 80 | 80 | 110 | 200 |
| 1 | D | 3 | 25 | 80 | 80 | 102.25 | 160 |
| 1 | D | 4 | 50 | 78.75 | 78.75 | 110 | 150 |

Table C.30: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Lateral vibration, part 2/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 1 | D | 5 | 50 | 100 | 100 | 112.5 | 160 |
| 1 | D | 6 | 75 | 100 | 100 | 142.5 | 200 |
| 1 | D | 7 | 70 | 107.5 | 107.5 | 156.25 | 210 |
| 1 | D | 8 | 75 | 120 | 120 | 176.25 | 250 |
| 1 | D | 9 | 110 | 136.25 | 136.25 | 200 | 350 |
| 1 | E | 1 | 50 | 60 | 60 | 100 | 250 |
| 1 | E | 2 | 30 | 67.5 | 67.5 | 100 | 120 |
| 1 | E | 3 | 50 | 90 | 90 | 111.25 | 150 |
| 1 | E | 4 | 50 | 80 | 80 | 135 | 200 |
| 1 | E | 5 | 45 | 100 | 100 | 130 | 180 |
| 1 | E | 6 | 75 | 100 | 100 | 130 | 300 |
| 1 | E | 7 | 100 | 120 | 120 | 150 | 300 |
| 1 | E | 8 | 80 | 120 | 120 | 176.25 | 300 |
| 1 | E | 9 | 70 | 110 | 110 | 180 | 200 |
| 1 | F | 1 | 40 | 75 | 75 | 110 | 150 |
| 1 | F | 2 | 45 | 70 | 70 | 100 | 150 |
| 1 | F | 3 | 30 | 78.75 | 78.75 | 120 | 150 |
| 1 | F | 4 | 25 | 78.75 | 78.75 | 107 | 150 |
| 1 | F | 5 | 25 | 100 | 100 | 150 | 200 |
| 1 | F | 6 | 75 | 115 | 115 | 150 | 200 |
| 1 | F | 7 | 50 | 120 | 120 | 176 | 200 |
| 1 | F | 8 | 75 | 120 | 120 | 175 | 265 |
| 1 | F | 9 | 110 | 133.75 | 133.75 | 192.5 | 253 |
| 1 | G | 1 | 10 | 70 | 70 | 102.5 | 150 |
| 1 | G | 2 | 25 | 80 | 80 | 100 | 150 |
| 1 | G | 3 | 50 | 95 | 95 | 140 | 300 |
| 1 | G | 4 | 70 | 100 | 100 | 150 | 200 |
| 1 | G | 5 | 60 | 97.25 | 97.25 | 125 | 250 |
| 1 | G | 6 | 75 | 117.75 | 117.75 | 152.5 | 300 |
| 1 | G | 7 | 100 | 137.5 | 137.5 | 180 | 300 |
| 1 | G | 8 | 100 | 128.75 | 128.75 | 200 | 400 |
| 1 | G | 9 | 100 | 128.75 | 128.75 | 200 | 400 |

Table C.31: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Lateral vibration, part 3/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | A | 1 | 20 | 50 | 50 | 80 | 100 |
| 8 | A | 2 | 40 | 50 | 50 | 82.5 | 100 |
| 8 | A | 3 | 50 | 80 | 80 | 100 | 100 |
| 8 | A | 4 | 70 | 90 | 90 | 100 | 110 |
| 8 | A | 5 | 50 | 100 | 100 | 100 | 150 |
| 8 | A | 6 | 100 | 100 | 100 | 102.5 | 120 |
| 8 | A | 7 | 90 | 100 | 100 | 112.5 | 130 |
| 8 | A | 8 | 100 | 100 | 100 | 130 | 160 |
| 8 | A | 9 | 100 | 120 | 120 | 150 | 150 |
| 8 | B | 1 | 20 | 50 | 50 | 81.75 | 120 |
| 8 | B | 2 | 30 | 68.75 | 68.75 | 100 | 108 |
| 8 | B | 3 | 50 | 65 | 65 | 100 | 140 |
| 8 | B | 4 | 50 | 80 | 80 | 104 | 130 |
| 8 | B | 5 | 60 | 100 | 100 | 120 | 150 |
| 8 | B | 6 | 65 | 95 | 95 | 132.5 | 200 |
| 8 | B | 7 | 75 | 103.75 | 103.75 | 132.5 | 180 |
| 8 | B | 8 | 80 | 128.75 | 128.75 | 177.5 | 217 |
| 8 | B | 9 | 100 | 138.75 | 138.75 | 170 | 206 |
| 8 | C | 1 | 20 | 50 | 50 | 100 | 120 |
| 8 | C | 2 | 50 | 80 | 80 | 110 | 125 |
| 8 | C | 3 | 35 | 75 | 75 | 101.25 | 130 |
| 8 | C | 4 | 70 | 87.5 | 87.5 | 102.5 | 150 |
| 8 | C | 5 | 40 | 93.75 | 93.75 | 125.5 | 170 |
| 8 | C | 6 | 75 | 113.75 | 113.75 | 150 | 211 |
| 8 | C | 7 | 90 | 110 | 110 | 150 | 215 |
| 8 | C | 8 | 120 | 123.75 | 123.75 | 152.5 | 250 |
| 8 | C | 9 | 110 | 140 | 140 | 190.5 | 250 |
| 8 | D | 1 | 25 | 50 | 50 | 100 | 120 |
| 8 | D | 2 | 50 | 80 | 80 | 102.5 | 130 |
| 8 | D | 3 | 50 | 78.75 | 78.75 | 102.5 | 130 |
| 8 | D | 4 | 50 | 98.75 | 98.75 | 120 | 160 |
| 8 | D | 5 | 50 | 100 | 100 | 125 | 150 |

Table C.32: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Lateral vibration, part 4/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | D | 6 | 100 | 110 | 110 | 142.5 | 200 |
| 8 | D | 7 | 75 | 120 | 120 | 162.25 | 200 |
| 8 | D | 8 | 120 | 128.75 | 128.75 | 170 | 254 |
| 8 | D | 9 | 75 | 147.5 | 147.5 | 200 | 269 |
| 8 | E | 1 | 20 | 57.5 | 57.5 | 92.5 | 130 |
| 8 | E | 2 | 35 | 78.75 | 78.75 | 110 | 150 |
| 8 | E | 3 | 50 | 80 | 80 | 110 | 130 |
| 8 | E | 4 | 50 | 100 | 100 | 120 | 150 |
| 8 | E | 5 | 75 | 100 | 100 | 135 | 200 |
| 8 | E | 6 | 90 | 118.75 | 118.75 | 152.5 | 200 |
| 8 | E | 7 | 80 | 120 | 120 | 157.5 | 250 |
| 8 | E | 8 | 120 | 128.75 | 128.75 | 185 | 266 |
| 8 | E | 9 | 120 | 130 | 130 | 200 | 300 |
| 8 | F | 1 | 25 | 50 | 50 | 90.25 | 125 |
| 8 | F | 2 | 50 | 78.75 | 78.75 | 102.5 | 120 |
| 8 | F | 3 | 25 | 80 | 80 | 121.25 | 159 |
| 8 | F | 4 | 50 | 80 | 80 | 130 | 200 |
| 8 | F | 5 | 100 | 117.5 | 117.5 | 150 | 155 |
| 8 | F | 6 | 75 | 117.5 | 117.5 | 152.5 | 200 |
| 8 | F | 7 | 75 | 125 | 125 | 150 | 200 |
| 8 | F | 8 | 95 | 125 | 125 | 182.5 | 300 |
| 8 | F | 9 | 130 | 150 | 150 | 185 | 300 |
| 8 | G | 1 | 20 | 57.5 | 57.5 | 110 | 147 |
| 8 | G | 2 | 25 | 73.75 | 73.75 | 112.5 | 160 |
| 8 | G | 3 | 40 | 75 | 75 | 120 | 206 |
| 8 | G | 4 | 50 | 97.5 | 97.5 | 132.5 | 199 |
| 8 | G | 5 | 75 | 88.75 | 88.75 | 150 | 211 |
| 8 | G | 6 | 50 | 117.5 | 117.5 | 152.5 | 250 |
| 8 | G | 7 | 85 | 120 | 120 | 152.5 | 231 |
| 8 | G | 8 | 100 | 140 | 140 | 192.5 | 226 |
| 8 | G | 9 | 125 | 150 | 150 | 185 | 300 |

Table C.33: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Vertical vibration, part 1/4)

| Freq (Hz) | Waveform | Mag. no. | min | 25 | 50 | 75 | max |
|---|---|---|---|---|---|---|---|
| 1 | A | 1 | 30 | 40.75 | 40.75 | 81.25 | 100 |
| 1 | A | 2 | 30 | 49.75 | 49.75 | 82.5 | 120 |
| 1 | A | 3 | 15 | 67.5 | 67.5 | 100 | 100 |
| 1 | A | 4 | 50 | 77.5 | 77.5 | 100 | 110 |
| 1 | A | 5 | 50 | 80 | 80 | 110 | 120 |
| 1 | A | 6 | 60 | 100 | 100 | 112.5 | 160 |
| 1 | A | 7 | 70 | 105 | 105 | 120 | 176 |
| 1 | A | 8 | 89 | 103.75 | 103.75 | 130 | 200 |
| 1 | A | 9 | 80 | 110 | 110 | 150 | 200 |
| 1 | B | 1 | 15 | 43.75 | 43.75 | 80 | 140 |
| 1 | B | 2 | 20 | 53 | 53 | 80 | 140 |
| 1 | B | 3 | 5 | 77.5 | 77.5 | 109.25 | 120 |
| 1 | B | 4 | 60 | 80 | 80 | 114 | 190 |
| 1 | B | 5 | 60 | 83.75 | 83.75 | 130 | 200 |
| 1 | B | 6 | 80 | 100 | 100 | 130 | 250 |
| 1 | B | 7 | 60 | 100 | 100 | 150 | 180 |
| 1 | B | 8 | 70 | 123.75 | 123.75 | 191.75 | 220 |
| 1 | B | 9 | 65 | 120 | 120 | 172.5 | 255 |
| 1 | C | 1 | 10 | 40 | 40 | 72.5 | 100 |
| 1 | C | 2 | 5 | 65 | 65 | 86.25 | 100 |
| 1 | C | 3 | 10 | 57.5 | 57.5 | 82.5 | 160 |
| 1 | C | 4 | 30 | 67.5 | 67.5 | 110 | 140 |
| 1 | C | 5 | 40 | 80 | 80 | 130 | 150 |
| 1 | C | 6 | 50 | 97.5 | 97.5 | 122.5 | 169 |
| 1 | C | 7 | 50 | 90.75 | 90.75 | 130 | 190 |
| 1 | C | 8 | 80 | 120 | 120 | 155 | 250 |
| 1 | C | 9 | 120 | 137.5 | 137.5 | 160 | 210 |
| 1 | D | 1 | 5 | 50 | 50 | 80 | 160 |
| 1 | D | 2 | 5 | 57.5 | 57.5 | 92.5 | 130 |
| 1 | D | 3 | 35 | 57.5 | 57.5 | 90 | 120 |
| 1 | D | 4 | 50 | 67.5 | 67.5 | 110 | 150 |

Table C.34: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Vertical vibration, part 2/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 1 | D | 5 | 40 | 80 | 80 | 120 | 210 |
| 1 | D | 6 | 40 | 90 | 90 | 132.5 | 175 |
| 1 | D | 7 | 70 | 97.5 | 97.5 | 140 | 200 |
| 1 | D | 8 | 80 | 120 | 120 | 150 | 295 |
| 1 | D | 9 | 110 | 128.75 | 128.75 | 180 | 250 |
| 1 | E | 1 | 15 | 40 | 40 | 80 | 120 |
| 1 | E | 2 | 10 | 57.5 | 57.5 | 100 | 200 |
| 1 | E | 3 | 20 | 75 | 75 | 90 | 157 |
| 1 | E | 4 | 40 | 78.75 | 78.75 | 112.5 | 150 |
| 1 | E | 5 | 60 | 80 | 80 | 142.5 | 210 |
| 1 | E | 6 | 50 | 97.5 | 97.5 | 142.5 | 220 |
| 1 | E | 7 | 85 | 115 | 115 | 150 | 255 |
| 1 | E | 8 | 80 | 120 | 120 | 150 | 325 |
| 1 | E | 9 | 110 | 127.5 | 127.5 | 200 | 400 |
| 1 | F | 1 | 10 | 36.75 | 36.75 | 80 | 130 |
| 1 | F | 2 | 10 | 50 | 50 | 90 | 100 |
| 1 | F | 3 | 10 | 43.75 | 43.75 | 120 | 200 |
| 1 | F | 4 | 20 | 67.5 | 67.5 | 110 | 150 |
| 1 | F | 5 | 20 | 77.5 | 77.5 | 120 | 190 |
| 1 | F | 6 | 20 | 87.5 | 87.5 | 140 | 180 |
| 1 | F | 7 | 70 | 110 | 110 | 152.5 | 292 |
| 1 | F | 8 | 80 | 120 | 120 | 152.5 | 300 |
| 1 | F | 9 | 110 | 128.75 | 128.75 | 200 | 450 |
| 1 | G | 1 | 20 | 40 | 40 | 102.5 | 120 |
| 1 | G | 2 | 5 | 38.75 | 38.75 | 85 | 140 |
| 1 | G | 3 | 25 | 55 | 55 | 110 | 150 |
| 1 | G | 4 | 40 | 80 | 80 | 127.5 | 182 |
| 1 | G | 5 | 20 | 87.5 | 87.5 | 130 | 199 |
| 1 | G | 6 | 60 | 97.5 | 97.5 | 142.5 | 257 |
| 1 | G | 7 | 70 | 110 | 110 | 165 | 300 |
| 1 | G | 8 | 90 | 110 | 110 | 172.5 | 358 |
| 1 | G | 9 | 90 | 120 | 120 | 200 | 350 |

Table C.35: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Vertical vibration, part 3/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | A | 1 | 20 | 60 | 60 | 90 | 95 |
| 8 | A | 2 | 30 | 70 | 70 | 90 | 100 |
| 8 | A | 3 | 40 | 80 | 80 | 100 | 110 |
| 8 | A | 4 | 60 | 90 | 90 | 100 | 120 |
| 8 | A | 5 | 80 | 87.5 | 87.5 | 100 | 120 |
| 8 | A | 6 | 90 | 100 | 100 | 102.5 | 169 |
| 8 | A | 7 | 80 | 100 | 100 | 116.25 | 150 |
| 8 | A | 8 | 90 | 100 | 100 | 116.25 | 190 |
| 8 | A | 9 | 100 | 100 | 100 | 122.5 | 200 |
| 8 | B | 1 | 10 | 47.5 | 47.5 | 80 | 110 |
| 8 | B | 2 | 20 | 68.75 | 68.75 | 91.25 | 100 |
| 8 | B | 3 | 50 | 67.5 | 67.5 | 100 | 122 |
| 8 | B | 4 | 60 | 80 | 80 | 100 | 156 |
| 8 | B | 5 | 50 | 80 | 80 | 120 | 195 |
| 8 | B | 6 | 40 | 80 | 80 | 120 | 170 |
| 8 | B | 7 | 60 | 97.5 | 97.5 | 120 | 150 |
| 8 | B | 8 | 80 | 100 | 100 | 142.5 | 157 |
| 8 | B | 9 | 70 | 110 | 110 | 132.5 | 189 |
| 8 | C | 1 | 20 | 50 | 50 | 90 | 120 |
| 8 | C | 2 | 30 | 73.75 | 73.75 | 92.25 | 120 |
| 8 | C | 3 | 40 | 88.75 | 88.75 | 120 | 130 |
| 8 | C | 4 | 35 | 87.5 | 87.5 | 122.5 | 190 |
| 8 | C | 5 | 60 | 100 | 100 | 120 | 179 |
| 8 | C | 6 | 40 | 100 | 100 | 120 | 147 |
| 8 | C | 7 | 60 | 95 | 95 | 140 | 180 |
| 8 | C | 8 | 60 | 100 | 100 | 142.5 | 160 |
| 8 | C | 9 | 110 | 120 | 120 | 160 | 256 |
| 8 | D | 1 | 20 | 60 | 60 | 80 | 135 |
| 8 | D | 2 | 30 | 68.75 | 68.75 | 110 | 204 |
| 8 | D | 3 | 30 | 78.75 | 78.75 | 100 | 135 |
| 8 | D | 4 | 40 | 80 | 80 | 120 | 187 |
| 8 | D | 5 | 50 | 83.75 | 83.75 | 122.5 | 180 |

Table C.36: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 7 with each test stimulus (Vertical vibration, part 4/4)

| Freq (Hz) | Waveform | Mag. no. | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|
| 8 | D | 6 | 70 | 97.5 | 97.5 | 130 | 160 |
| 8 | D | 7 | 80 | 110 | 110 | 149.25 | 190 |
| 8 | D | 8 | 110 | 110 | 110 | 130 | 200 |
| 8 | D | 9 | 110 | 120 | 120 | 165 | 205 |
| 8 | E | 1 | 20 | 57.5 | 57.5 | 90 | 140 |
| 8 | E | 2 | 20 | 57.5 | 57.5 | 112.5 | 172 |
| 8 | E | 3 | 30 | 80 | 80 | 114 | 160 |
| 8 | E | 4 | 50 | 83.75 | 83.75 | 110 | 139 |
| 8 | E | 5 | 50 | 88.75 | 88.75 | 120 | 187 |
| 8 | E | 6 | 60 | 110 | 110 | 150 | 185 |
| 8 | E | 7 | 50 | 110 | 110 | 140 | 170 |
| 8 | E | 8 | 80 | 120 | 120 | 142.5 | 280 |
| 8 | E | 9 | 105 | 130 | 130 | 176.25 | 231 |
| 8 | F | 1 | 20 | 48.75 | 48.75 | 90 | 140 |
| 8 | F | 2 | 30 | 80 | 80 | 110 | 198 |
| 8 | F | 3 | 40 | 88.75 | 88.75 | 120 | 170 |
| 8 | F | 4 | 50 | 83.75 | 83.75 | 132.5 | 180 |
| 8 | F | 5 | 40 | 88.75 | 88.75 | 132.5 | 212 |
| 8 | F | 6 | 40 | 100 | 100 | 150 | 200 |
| 8 | F | 7 | 70 | 110 | 110 | 142.5 | 189 |
| 8 | F | 8 | 90 | 127.5 | 127.5 | 162.5 | 200 |
| 8 | F | 9 | 80 | 123.75 | 123.75 | 172.5 | 348 |
| 8 | G | 1 | 20 | 56.25 | 56.25 | 110 | 189 |
| 8 | G | 2 | 20 | 70 | 70 | 100 | 120 |
| 8 | G | 3 | 20 | 77.5 | 77.5 | 120 | 130 |
| 8 | G | 4 | 40 | 80 | 80 | 130 | 189 |
| 8 | G | 5 | 40 | 90 | 90 | 120 | 172 |
| 8 | G | 6 | 65 | 95 | 95 | 132.5 | 200 |
| 8 | G | 7 | 50 | 107.5 | 107.5 | 132.5 | 196 |
| 8 | G | 8 | 80 | 120 | 120 | 160 | 230 |
| 8 | G | 9 | 60 | 112.5 | 112.5 | 170 | 202 |

## C.5 Chapter 8

Table C.37: Summary (minimum, 25th percentile, median, 75th percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 1/8)

| Freq. (Hz) | Mag no. x | Mag no. y | Mag no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 5 | 30 | 30 | 50 | 80 |
| 1 | 1 | 1 | 3 | 10 | 38 | 80 | 90 | 100 |
| 1 | 1 | 1 | 4 | 60 | 90 | 100 | 120 | 190 |
| 1 | 1 | 1 | 5 | 75 | 130 | 155 | 175 | 250 |
| 1 | 1 | 2 | 1 | 3 | 30 | 50 | 63 | 200 |
| 1 | 1 | 2 | 2 | 40 | 50 | 80 | 83 | 110 |
| 1 | 1 | 2 | 3 | 70 | 88 | 100 | 110 | 180 |
| 1 | 1 | 2 | 4 | 60 | 100 | 110 | 120 | 190 |
| 1 | 1 | 2 | 5 | 60 | 128 | 135 | 153 | 300 |
| 1 | 1 | 3 | 1 | 20 | 50 | 75 | 90 | 140 |
| 1 | 1 | 3 | 2 | 30 | 60 | 80 | 90 | 120 |
| 1 | 1 | 3 | 3 | 60 | 100 | 100 | 113 | 120 |
| 1 | 1 | 3 | 4 | 30 | 108 | 120 | 143 | 200 |
| 1 | 1 | 3 | 5 | 110 | 128 | 150 | 183 | 300 |
| 1 | 1 | 4 | 1 | 60 | 90 | 105 | 120 | 250 |
| 1 | 1 | 4 | 2 | 80 | 100 | 120 | 123 | 150 |
| 1 | 1 | 4 | 3 | 70 | 100 | 110 | 120 | 130 |
| 1 | 1 | 4 | 4 | 100 | 114 | 120 | 130 | 200 |
| 1 | 1 | 4 | 5 | 100 | 130 | 160 | 200 | 300 |
| 1 | 1 | 5 | 1 | 70 | 108 | 135 | 143 | 180 |
| 1 | 1 | 5 | 2 | 110 | 120 | 130 | 165 | 450 |
| 1 | 1 | 5 | 3 | 50 | 109 | 125 | 143 | 200 |
| 1 | 1 | 5 | 4 | 70 | 130 | 170 | 193 | 300 |
| 1 | 1 | 5 | 5 | 120 | 178 | 205 | 258 | 400 |
| 1 | 2 | 1 | 1 | 10 | 20 | 35 | 54 | 100 |
| 1 | 2 | 1 | 2 | 30 | 65 | 80 | 100 | 110 |
| 1 | 2 | 1 | 3 | 30 | 70 | 90 | 93 | 110 |
| 1 | 2 | 1 | 4 | 70 | 90 | 105 | 143 | 180 |
| 1 | 2 | 1 | 5 | 100 | 130 | 155 | 173 | 300 |
| 1 | 2 | 2 | 1 | 25 | 48 | 60 | 83 | 100 |
| 1 | 2 | 2 | 2 | 40 | 80 | 90 | 100 | 110 |

Table C.38: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 2/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 2 | 3 | 70 | 80 | 100 | 110 | 150 |
| 1 | 2 | 2 | 4 | 50 | 100 | 110 | 123 | 210 |
| 1 | 2 | 2 | 5 | 100 | 138 | 150 | 200 | 300 |
| 1 | 2 | 3 | 1 | 30 | 68 | 80 | 93 | 120 |
| 1 | 2 | 3 | 2 | 30 | 80 | 95 | 110 | 120 |
| 1 | 2 | 3 | 3 | 70 | 100 | 100 | 110 | 140 |
| 1 | 2 | 3 | 4 | 90 | 120 | 120 | 143 | 200 |
| 1 | 2 | 3 | 5 | 100 | 148 | 150 | 180 | 250 |
| 1 | 2 | 4 | 1 | 60 | 90 | 110 | 120 | 220 |
| 1 | 2 | 4 | 2 | 75 | 100 | 110 | 130 | 150 |
| 1 | 2 | 4 | 3 | 80 | 120 | 140 | 153 | 250 |
| 1 | 2 | 4 | 4 | 100 | 118 | 128 | 160 | 200 |
| 1 | 2 | 4 | 5 | 120 | 140 | 155 | 190 | 300 |
| 1 | 2 | 5 | 1 | 100 | 120 | 145 | 180 | 210 |
| 1 | 2 | 5 | 2 | 120 | 130 | 150 | 163 | 250 |
| 1 | 2 | 5 | 3 | 110 | 120 | 145 | 183 | 300 |
| 1 | 2 | 5 | 4 | 120 | 138 | 150 | 173 | 280 |
| 1 | 2 | 5 | 5 | 20 | 138 | 170 | 208 | 350 |
| 1 | 3 | 1 | 1 | 20 | 48 | 70 | 93 | 150 |
| 1 | 3 | 1 | 2 | 60 | 80 | 95 | 100 | 120 |
| 1 | 3 | 1 | 3 | 50 | 88 | 100 | 113 | 160 |
| 1 | 3 | 1 | 4 | 60 | 108 | 112 | 120 | 150 |
| 1 | 3 | 1 | 5 | 110 | 130 | 150 | 163 | 250 |
| 1 | 3 | 2 | 1 | 30 | 68 | 90 | 100 | 140 |
| 1 | 3 | 2 | 2 | 70 | 88 | 100 | 113 | 300 |
| 1 | 3 | 2 | 3 | 80 | 90 | 120 | 123 | 200 |
| 1 | 3 | 2 | 4 | 90 | 108 | 115 | 138 | 200 |
| 1 | 3 | 2 | 5 | 110 | 128 | 155 | 163 | 200 |
| 1 | 3 | 3 | 1 | 40 | 70 | 80 | 103 | 120 |
| 1 | 3 | 3 | 2 | 60 | 100 | 110 | 123 | 150 |
| 1 | 3 | 3 | 3 | 40 | 110 | 130 | 133 | 200 |

Table C.39: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 3/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 3 | 4 | 100 | 118 | 130 | 150 | 200 |
| 1 | 3 | 3 | 5 | 140 | 158 | 178 | 180 | 320 |
| 1 | 3 | 4 | 1 | 70 | 89 | 100 | 130 | 180 |
| 1 | 3 | 4 | 2 | 100 | 118 | 120 | 150 | 180 |
| 1 | 3 | 4 | 3 | 100 | 128 | 145 | 185 | 270 |
| 1 | 3 | 4 | 4 | 100 | 120 | 130 | 153 | 200 |
| 1 | 3 | 4 | 5 | 120 | 148 | 165 | 200 | 350 |
| 1 | 3 | 5 | 1 | 60 | 120 | 130 | 158 | 250 |
| 1 | 3 | 5 | 2 | 100 | 120 | 130 | 205 | 220 |
| 1 | 3 | 5 | 3 | 80 | 120 | 130 | 150 | 250 |
| 1 | 3 | 5 | 4 | 120 | 150 | 177 | 213 | 350 |
| 1 | 3 | 5 | 5 | 130 | 168 | 190 | 258 | 350 |
| 1 | 4 | 1 | 1 | 60 | 95 | 105 | 123 | 300 |
| 1 | 4 | 1 | 2 | 50 | 98 | 120 | 130 | 150 |
| 1 | 4 | 1 | 3 | 60 | 98 | 110 | 120 | 200 |
| 1 | 4 | 1 | 4 | 90 | 120 | 135 | 153 | 250 |
| 1 | 4 | 1 | 5 | 120 | 140 | 175 | 200 | 300 |
| 1 | 4 | 2 | 1 | 80 | 90 | 130 | 155 | 200 |
| 1 | 4 | 2 | 2 | 75 | 100 | 115 | 123 | 175 |
| 1 | 4 | 2 | 3 | 80 | 108 | 120 | 145 | 200 |
| 1 | 4 | 2 | 4 | 100 | 138 | 160 | 193 | 350 |
| 1 | 4 | 2 | 5 | 110 | 148 | 180 | 205 | 300 |
| 1 | 4 | 3 | 1 | 50 | 78 | 105 | 120 | 200 |
| 1 | 4 | 3 | 2 | 100 | 110 | 123 | 150 | 180 |
| 1 | 4 | 3 | 3 | 80 | 118 | 130 | 153 | 300 |
| 1 | 4 | 3 | 4 | 100 | 120 | 140 | 170 | 250 |
| 1 | 4 | 3 | 5 | 50 | 148 | 160 | 185 | 300 |
| 1 | 4 | 4 | 1 | 95 | 118 | 140 | 150 | 300 |
| 1 | 4 | 4 | 2 | 100 | 120 | 140 | 158 | 250 |
| 1 | 4 | 4 | 3 | 100 | 120 | 150 | 205 | 300 |
| 1 | 4 | 4 | 4 | 110 | 138 | 165 | 185 | 250 |

Table C.40: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 4/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 4 | 5 | 140 | 160 | 180 | 200 | 300 |
| 1 | 4 | 5 | 1 | 100 | 120 | 130 | 150 | 200 |
| 1 | 4 | 5 | 2 | 120 | 140 | 160 | 193 | 250 |
| 1 | 4 | 5 | 3 | 100 | 128 | 150 | 180 | 220 |
| 1 | 4 | 5 | 4 | 130 | 140 | 180 | 203 | 300 |
| 1 | 4 | 5 | 5 | 120 | 168 | 190 | 213 | 400 |
| 1 | 5 | 1 | 1 | 90 | 139 | 160 | 200 | 350 |
| 1 | 5 | 1 | 2 | 120 | 140 | 150 | 185 | 300 |
| 1 | 5 | 1 | 3 | 100 | 120 | 155 | 180 | 275 |
| 1 | 5 | 1 | 4 | 130 | 150 | 200 | 250 | 400 |
| 1 | 5 | 1 | 5 | 140 | 170 | 200 | 285 | 350 |
| 1 | 5 | 2 | 1 | 100 | 140 | 155 | 178 | 300 |
| 1 | 5 | 2 | 2 | 120 | 128 | 150 | 165 | 280 |
| 1 | 5 | 2 | 3 | 110 | 138 | 185 | 228 | 300 |
| 1 | 5 | 2 | 4 | 120 | 158 | 180 | 223 | 300 |
| 1 | 5 | 2 | 5 | 140 | 174 | 200 | 250 | 400 |
| 1 | 5 | 3 | 1 | 100 | 148 | 200 | 285 | 400 |
| 1 | 5 | 3 | 2 | 40 | 128 | 150 | 183 | 350 |
| 1 | 5 | 3 | 3 | 130 | 160 | 200 | 263 | 350 |
| 1 | 5 | 3 | 4 | 120 | 158 | 180 | 255 | 300 |
| 1 | 5 | 3 | 5 | 140 | 150 | 183 | 228 | 400 |
| 1 | 5 | 4 | 1 | 70 | 120 | 180 | 233 | 300 |
| 1 | 5 | 4 | 2 | 120 | 158 | 190 | 223 | 300 |
| 1 | 5 | 4 | 3 | 110 | 144 | 180 | 200 | 300 |
| 1 | 5 | 4 | 4 | 130 | 163 | 180 | 203 | 350 |
| 1 | 5 | 4 | 5 | 140 | 168 | 190 | 203 | 350 |
| 1 | 5 | 5 | 1 | 120 | 160 | 200 | 250 | 300 |
| 1 | 5 | 5 | 2 | 120 | 158 | 180 | 213 | 300 |
| 1 | 5 | 5 | 3 | 120 | 188 | 200 | 263 | 450 |
| 1 | 5 | 5 | 4 | 140 | 185 | 200 | 223 | 300 |
| 1 | 5 | 5 | 5 | 140 | 190 | 235 | 300 | 400 |

Table C.41: Summary (minimum, 25$^{th}$ percentile, median, 75$^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 5/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 1 | 2 | 20 | 20 | 60 | 70 | 110 |
| 4 | 1 | 1 | 3 | 18 | 78 | 100 | 113 | 120 |
| 4 | 1 | 1 | 4 | 100 | 110 | 120 | 123 | 170 |
| 4 | 1 | 1 | 5 | 120 | 130 | 140 | 176 | 250 |
| 4 | 1 | 2 | 1 | 10 | 20 | 28 | 53 | 80 |
| 4 | 1 | 2 | 2 | 20 | 45 | 65 | 80 | 100 |
| 4 | 1 | 2 | 3 | 40 | 78 | 100 | 103 | 130 |
| 4 | 1 | 2 | 4 | 90 | 108 | 120 | 133 | 200 |
| 4 | 1 | 2 | 5 | 90 | 128 | 150 | 180 | 250 |
| 4 | 1 | 3 | 1 | 15 | 38 | 50 | 75 | 90 |
| 4 | 1 | 3 | 2 | 40 | 78 | 85 | 100 | 120 |
| 4 | 1 | 3 | 3 | 70 | 98 | 100 | 113 | 160 |
| 4 | 1 | 3 | 4 | 20 | 100 | 120 | 133 | 150 |
| 4 | 1 | 3 | 5 | 110 | 130 | 150 | 160 | 300 |
| 4 | 1 | 4 | 1 | 25 | 48 | 70 | 83 | 100 |
| 4 | 1 | 4 | 2 | 50 | 89 | 97 | 103 | 125 |
| 4 | 1 | 4 | 3 | 80 | 98 | 105 | 110 | 130 |
| 4 | 1 | 4 | 4 | 90 | 110 | 120 | 133 | 200 |
| 4 | 1 | 4 | 5 | 100 | 139 | 150 | 185 | 300 |
| 4 | 1 | 5 | 1 | 14 | 88 | 100 | 110 | 150 |
| 4 | 1 | 5 | 2 | 70 | 90 | 100 | 110 | 130 |
| 4 | 1 | 5 | 3 | 70 | 100 | 120 | 120 | 140 |
| 4 | 1 | 5 | 4 | 100 | 124 | 135 | 150 | 200 |
| 4 | 1 | 5 | 5 | 110 | 148 | 165 | 208 | 350 |
| 4 | 2 | 1 | 1 | 5 | 28 | 35 | 50 | 90 |
| 4 | 2 | 1 | 2 | 20 | 58 | 80 | 93 | 110 |
| 4 | 2 | 1 | 3 | 50 | 90 | 98 | 100 | 130 |
| 4 | 2 | 1 | 4 | 50 | 100 | 115 | 123 | 150 |
| 4 | 2 | 1 | 5 | 90 | 130 | 150 | 160 | 300 |
| 4 | 2 | 2 | 1 | 20 | 30 | 50 | 65 | 100 |
| 4 | 2 | 2 | 2 | 20 | 69 | 80 | 90 | 110 |

Table C.42: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 6/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 4 | 2 | 2 | 3 | 50 | 100 | 100 | 103 | 180 |
| 4 | 2 | 2 | 4 | 100 | 110 | 120 | 133 | 200 |
| 4 | 2 | 2 | 5 | 100 | 130 | 140 | 160 | 200 |
| 4 | 2 | 3 | 1 | 9 | 45 | 70 | 80 | 100 |
| 4 | 2 | 3 | 2 | 35 | 84 | 100 | 100 | 120 |
| 4 | 2 | 3 | 3 | 60 | 96 | 100 | 100 | 120 |
| 4 | 2 | 3 | 4 | 100 | 110 | 113 | 133 | 170 |
| 4 | 2 | 3 | 5 | 100 | 130 | 150 | 155 | 250 |
| 4 | 2 | 4 | 1 | 30 | 50 | 75 | 83 | 110 |
| 4 | 2 | 4 | 2 | 89 | 90 | 100 | 110 | 120 |
| 4 | 2 | 4 | 3 | 90 | 90 | 100 | 100 | 150 |
| 4 | 2 | 4 | 4 | 100 | 108 | 115 | 130 | 160 |
| 4 | 2 | 4 | 5 | 90 | 120 | 150 | 183 | 350 |
| 4 | 2 | 5 | 1 | 40 | 90 | 100 | 125 | 200 |
| 4 | 2 | 5 | 2 | 90 | 100 | 110 | 130 | 150 |
| 4 | 2 | 5 | 3 | 90 | 110 | 110 | 120 | 150 |
| 4 | 2 | 5 | 4 | 100 | 120 | 130 | 136 | 170 |
| 4 | 2 | 5 | 5 | 120 | 138 | 155 | 193 | 300 |
| 4 | 3 | 1 | 1 | 30 | 50 | 50 | 63 | 100 |
| 4 | 3 | 1 | 2 | 50 | 74 | 80 | 100 | 110 |
| 4 | 3 | 1 | 3 | 60 | 98 | 100 | 110 | 130 |
| 4 | 3 | 1 | 4 | 40 | 110 | 125 | 153 | 200 |
| 4 | 3 | 1 | 5 | 100 | 128 | 145 | 160 | 350 |
| 4 | 3 | 2 | 1 | 30 | 50 | 70 | 93 | 130 |
| 4 | 3 | 2 | 2 | 40 | 78 | 90 | 100 | 120 |
| 4 | 3 | 2 | 3 | 90 | 100 | 105 | 110 | 130 |
| 4 | 3 | 2 | 4 | 100 | 110 | 120 | 133 | 220 |
| 4 | 3 | 2 | 5 | 90 | 138 | 155 | 185 | 300 |
| 4 | 3 | 3 | 1 | 60 | 70 | 83 | 90 | 120 |
| 4 | 3 | 3 | 2 | 20 | 90 | 100 | 103 | 120 |
| 4 | 3 | 3 | 3 | 100 | 100 | 110 | 120 | 200 |

Table C.43: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 7/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 4 | 3 | 3 | 4 | 90 | 108 | 120 | 133 | 200 |
| 4 | 3 | 3 | 5 | 120 | 150 | 160 | 173 | 250 |
| 4 | 3 | 4 | 1 | 60 | 78 | 95 | 103 | 120 |
| 4 | 3 | 4 | 2 | 70 | 90 | 100 | 100 | 120 |
| 4 | 3 | 4 | 3 | 70 | 100 | 110 | 113 | 120 |
| 4 | 3 | 4 | 4 | 100 | 110 | 120 | 143 | 200 |
| 4 | 3 | 4 | 5 | 110 | 130 | 140 | 170 | 250 |
| 4 | 3 | 5 | 1 | 70 | 90 | 100 | 110 | 170 |
| 4 | 3 | 5 | 2 | 50 | 100 | 100 | 120 | 140 |
| 4 | 3 | 5 | 3 | 50 | 100 | 120 | 130 | 150 |
| 4 | 3 | 5 | 4 | 120 | 138 | 150 | 163 | 200 |
| 4 | 3 | 5 | 5 | 140 | 150 | 163 | 220 | 350 |
| 4 | 4 | 1 | 1 | 50 | 78 | 90 | 100 | 200 |
| 4 | 4 | 1 | 2 | 70 | 90 | 100 | 110 | 130 |
| 4 | 4 | 1 | 3 | 80 | 98 | 110 | 123 | 175 |
| 4 | 4 | 1 | 4 | 50 | 118 | 120 | 139 | 160 |
| 4 | 4 | 1 | 5 | 120 | 150 | 160 | 180 | 300 |
| 4 | 4 | 2 | 1 | 60 | 80 | 90 | 103 | 120 |
| 4 | 4 | 2 | 2 | 95 | 100 | 110 | 113 | 160 |
| 4 | 4 | 2 | 3 | 50 | 100 | 110 | 120 | 170 |
| 4 | 4 | 2 | 4 | 100 | 110 | 120 | 133 | 170 |
| 4 | 4 | 2 | 5 | 110 | 148 | 160 | 180 | 300 |
| 4 | 4 | 3 | 1 | 60 | 78 | 88 | 100 | 120 |
| 4 | 4 | 3 | 2 | 80 | 89 | 105 | 110 | 130 |
| 4 | 4 | 3 | 3 | 90 | 100 | 110 | 120 | 150 |
| 4 | 4 | 3 | 4 | 100 | 110 | 120 | 145 | 200 |
| 4 | 4 | 3 | 5 | 130 | 140 | 155 | 193 | 300 |
| 4 | 4 | 4 | 1 | 60 | 80 | 100 | 100 | 120 |
| 4 | 4 | 4 | 2 | 80 | 95 | 105 | 120 | 130 |
| 4 | 4 | 4 | 3 | 70 | 100 | 100 | 123 | 170 |
| 4 | 4 | 4 | 4 | 100 | 118 | 125 | 173 | 220 |

Table C.44: Summary (minimum, 25th percentile, median, 75th percentile and maximum) of the raw data obtained with the method of magnitude estimation in Chapter 8 with each test stimulus (part 8/8)

| Freq. (Hz) | Mag. no. x | Mag. no. y | Mag. no. z | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|---|---|
| 4 | 4 | 4 | 5 | 100 | 140 | 150 | 180 | 250 |
| 4 | 4 | 5 | 1 | 70 | 100 | 120 | 133 | 160 |
| 4 | 4 | 5 | 2 | 90 | 108 | 120 | 143 | 300 |
| 4 | 4 | 5 | 3 | 90 | 108 | 130 | 140 | 220 |
| 4 | 4 | 5 | 4 | 100 | 120 | 145 | 163 | 250 |
| 4 | 4 | 5 | 5 | 120 | 158 | 160 | 213 | 310 |
| 4 | 5 | 1 | 1 | 80 | 100 | 105 | 130 | 170 |
| 4 | 5 | 1 | 2 | 90 | 110 | 120 | 140 | 180 |
| 4 | 5 | 1 | 3 | 60 | 110 | 125 | 150 | 200 |
| 4 | 5 | 1 | 4 | 70 | 120 | 140 | 165 | 250 |
| 4 | 5 | 1 | 5 | 100 | 138 | 170 | 200 | 250 |
| 4 | 5 | 2 | 1 | 90 | 110 | 115 | 126 | 250 |
| 4 | 5 | 2 | 2 | 100 | 110 | 120 | 130 | 200 |
| 4 | 5 | 2 | 3 | 70 | 118 | 130 | 170 | 220 |
| 4 | 5 | 2 | 4 | 110 | 120 | 140 | 153 | 250 |
| 4 | 5 | 2 | 5 | 110 | 148 | 165 | 213 | 280 |
| 4 | 5 | 3 | 1 | 60 | 100 | 115 | 135 | 170 |
| 4 | 5 | 3 | 2 | 70 | 110 | 130 | 156 | 200 |
| 4 | 5 | 3 | 3 | 110 | 120 | 130 | 150 | 250 |
| 4 | 5 | 3 | 4 | 90 | 120 | 145 | 163 | 220 |
| 4 | 5 | 3 | 5 | 120 | 150 | 180 | 200 | 400 |
| 4 | 5 | 4 | 1 | 100 | 120 | 140 | 150 | 200 |
| 4 | 5 | 4 | 2 | 100 | 120 | 135 | 150 | 230 |
| 4 | 5 | 4 | 3 | 110 | 120 | 125 | 163 | 200 |
| 4 | 5 | 4 | 4 | 120 | 148 | 155 | 180 | 230 |
| 4 | 5 | 4 | 5 | 120 | 149 | 160 | 200 | 320 |
| 4 | 5 | 5 | 1 | 100 | 120 | 135 | 160 | 400 |
| 4 | 5 | 5 | 2 | 100 | 128 | 140 | 178 | 300 |
| 4 | 5 | 5 | 3 | 100 | 120 | 140 | 153 | 230 |
| 4 | 5 | 5 | 4 | 120 | 130 | 150 | 180 | 250 |
| 4 | 5 | 5 | 5 | 120 | 148 | 160 | 193 | 350 |

# Appendix D

# Linear regression quality

In this section, the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the physical magnitudes (acceleration) and the logarithms of the subjective magnitudes (magnitude estimates, see Appendix C) are summarized.

## D.1 Chapter 4

Table D.1: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the objective and subjective magnitudes in Chapter 4: Fore-and-aft vibration.

| Freq. (Hz) | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|
| 0.5 | 0.25 | 0.68 | 0.76 | 0.84 | 0.96 |
| 0.63 | 0.33 | 0.67 | 0.76 | 0.89 | 0.97 |
| 0.8 | 0.49 | 0.58 | 0.65 | 0.82 | 0.98 |
| 1 | 0.14 | 0.70 | 0.82 | 0.90 | 0.94 |
| 1.25 | 0.15 | 0.52 | 0.78 | 0.84 | 0.92 |
| 1.6 | 0.09 | 0.63 | 0.80 | 0.86 | 0.92 |
| 2 | 0.30 | 0.67 | 0.78 | 0.87 | 0.95 |
| 2.5 | 0.11 | 0.63 | 0.78 | 0.84 | 0.96 |
| 3.15 | 0.29 | 0.66 | 0.78 | 0.83 | 0.91 |
| 4 | 0.26 | 0.76 | 0.82 | 0.88 | 0.94 |
| 5 | 0.48 | 0.69 | 0.78 | 0.86 | 0.94 |
| 6.3 | 0.36 | 0.69 | 0.73 | 0.84 | 0.94 |
| 8 | 0.00 | 0.57 | 0.67 | 0.77 | 0.87 |
| 10 | 0.43 | 0.61 | 0.78 | 0.82 | 0.91 |
| 12.5 | 0.09 | 0.68 | 0.83 | 0.86 | 0.92 |
| 16 | 0.10 | 0.58 | 0.81 | 0.90 | 0.94 |

Table D.2: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the objective and subjective magnitudes in Chapter 4: Lateral vibration.

| Freq. (Hz) | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|
| 0.5 | 0.36 | 0.57 | 0.75 | 0.89 | 0.96 |
| 0.63 | 0.08 | 0.55 | 0.64 | 0.73 | 0.95 |
| 0.8 | 0.25 | 0.59 | 0.69 | 0.78 | 0.88 |
| 1 | 0.27 | 0.63 | 0.75 | 0.85 | 0.91 |
| 1.25 | 0.50 | 0.59 | 0.73 | 0.82 | 0.94 |
| 1.6 | 0.37 | 0.63 | 0.77 | 0.82 | 0.94 |
| 2 | 0.53 | 0.69 | 0.81 | 0.85 | 0.93 |
| 2.5 | 0.15 | 0.56 | 0.80 | 0.87 | 0.98 |
| 3.15 | 0.40 | 0.51 | 0.72 | 0.83 | 0.87 |
| 4 | 0.18 | 0.69 | 0.76 | 0.85 | 0.97 |
| 5 | 0.42 | 0.61 | 0.84 | 0.86 | 0.95 |
| 6.3 | 0.57 | 0.66 | 0.77 | 0.82 | 0.92 |
| 8 | 0.45 | 0.62 | 0.77 | 0.83 | 0.96 |
| 10 | 0.51 | 0.67 | 0.74 | 0.85 | 0.94 |
| 12.5 | 0.46 | 0.56 | 0.71 | 0.85 | 0.88 |
| 16 | 0.54 | 0.72 | 0.84 | 0.87 | 0.93 |

Table D.3: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the objective and subjective magnitudes in Chapter 4: Vertical vibration.

| Freq. (Hz) | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|
| 0.5 | 0.59 | 0.78 | 0.88 | 0.90 | 0.95 |
| 0.63 | 0.43 | 0.74 | 0.79 | 0.90 | 0.96 |
| 0.8 | 0.46 | 0.81 | 0.87 | 0.90 | 0.98 |
| 1 | 0.41 | 0.82 | 0.86 | 0.93 | 0.96 |
| 1.25 | 0.46 | 0.77 | 0.83 | 0.90 | 0.97 |
| 1.6 | 0.16 | 0.80 | 0.84 | 0.90 | 0.96 |
| 2 | 0.55 | 0.74 | 0.82 | 0.92 | 0.97 |
| 2.5 | 0.54 | 0.81 | 0.86 | 0.90 | 0.96 |
| 3.15 | 0.40 | 0.72 | 0.88 | 0.91 | 0.97 |
| 4 | 0.60 | 0.74 | 0.81 | 0.89 | 0.95 |
| 5 | 0.47 | 0.78 | 0.85 | 0.89 | 0.95 |
| 6.3 | 0.21 | 0.61 | 0.72 | 0.86 | 0.97 |
| 8 | 0.24 | 0.70 | 0.82 | 0.88 | 0.94 |
| 10 | 0.54 | 0.70 | 0.80 | 0.91 | 0.95 |
| 12.5 | 0.56 | 0.73 | 0.85 | 0.91 | 0.96 |
| 16 | 0.57 | 0.73 | 0.81 | 0.87 | 0.93 |

## D.2 Chapter 6

Table D.4: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the objective and subjective magnitudes in Chapter 6: Fore-and-aft vibration.

| Support | Freq. (Hz) | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| Free | 0.5 | 0.59 | 0.94 | 0.96 | 0.98 | 0.99 |
| Free | 1 | 0.62 | 0.87 | 0.92 | 0.95 | 1.00 |
| Free | 2 | 0.46 | 0.90 | 0.95 | 0.96 | 0.99 |
| Free | 4 | 0.55 | 0.84 | 0.90 | 0.94 | 0.99 |
| Free | 8 | 0.71 | 0.85 | 0.92 | 0.96 | 0.99 |
| Free | 16 | 0.45 | 0.79 | 0.89 | 0.93 | 1.00 |
| Bar | 0.5 | 0.63 | 0.71 | 0.85 | 0.93 | 0.99 |
| Bar | 1 | 0.79 | 0.84 | 0.89 | 0.92 | 0.98 |
| Bar | 2 | 0.49 | 0.78 | 0.91 | 0.95 | 0.99 |
| Bar | 4 | 0.68 | 0.83 | 0.92 | 0.98 | 0.99 |
| Bar | 8 | 0.84 | 0.91 | 0.94 | 0.95 | 0.98 |
| Bar | 16 | 0.61 | 0.85 | 0.90 | 0.95 | 0.97 |
| Shoulder | 0.5 | 0.59 | 0.78 | 0.84 | 0.95 | 0.98 |
| Shoulder | 1 | 0.63 | 0.87 | 0.91 | 0.94 | 0.97 |
| Shoulder | 2 | 0.74 | 0.91 | 0.94 | 0.97 | 0.99 |
| Shoulder | 4 | 0.57 | 0.91 | 0.93 | 0.95 | 0.98 |
| Shoulder | 8 | 0.58 | 0.82 | 0.94 | 0.98 | 0.99 |
| Shoulder | 16 | 0.61 | 0.87 | 0.92 | 0.95 | 0.97 |
| Back | 0.5 | 0.70 | 0.75 | 0.87 | 0.96 | 0.99 |
| Back | 1 | 0.57 | 0.85 | 0.91 | 0.95 | 0.99 |
| Back | 2 | 0.00 | 0.64 | 0.91 | 0.95 | 0.99 |
| Back | 4 | 0.71 | 0.77 | 0.88 | 0.98 | 1.00 |
| Back | 8 | 0.41 | 0.71 | 0.87 | 0.94 | 0.98 |
| Back | 16 | 0.43 | 0.86 | 0.93 | 0.95 | 0.98 |

Table D.5: Summary (minimum, $25^{th}$ percentile, median, $75^{th}$ percentile and maximum) of the coefficients of determination, $R^2$, obtained in linear regressions between the logarithms of the objective and subjective magnitudes in Chapter 6: Lateral vibration.

| Support | Freq. (Hz) | Min. | 25th p. | Median | 75th p. | Max. |
|---|---|---|---|---|---|---|
| Free | 0.5 | 0.68 | 0.79 | 0.84 | 0.95 | 0.99 |
| Free | 1 | 0.03 | 0.88 | 0.92 | 0.94 | 0.98 |
| Free | 2 | 0.58 | 0.83 | 0.91 | 0.97 | 0.99 |
| Free | 4 | 0.54 | 0.81 | 0.83 | 0.92 | 0.99 |
| Free | 8 | 0.49 | 0.78 | 0.84 | 0.88 | 0.94 |
| Free | 16 | 0.70 | 0.81 | 0.88 | 0.92 | 0.96 |
| Bar | 0.5 | 0.47 | 0.64 | 0.73 | 0.93 | 0.99 |
| Bar | 1 | 0.60 | 0.75 | 0.89 | 0.92 | 0.99 |
| Bar | 2 | 0.74 | 0.84 | 0.93 | 0.96 | 0.99 |
| Bar | 4 | 0.34 | 0.83 | 0.92 | 0.97 | 0.99 |
| Bar | 8 | 0.67 | 0.91 | 0.93 | 0.96 | 0.99 |
| Bar | 16 | 0.42 | 0.71 | 0.87 | 0.92 | 0.98 |
| Shoulder | 0.5 | 0.41 | 0.77 | 0.86 | 0.92 | 0.98 |
| Shoulder | 1 | 0.70 | 0.77 | 0.84 | 0.94 | 0.99 |
| Shoulder | 2 | 0.75 | 0.81 | 0.90 | 0.96 | 0.99 |
| Shoulder | 4 | 0.36 | 0.81 | 0.90 | 0.95 | 0.99 |
| Shoulder | 8 | 0.26 | 0.78 | 0.91 | 0.95 | 0.98 |
| Shoulder | 16 | 0.66 | 0.77 | 0.91 | 0.96 | 0.99 |
| Back | 0.5 | 0.62 | 0.84 | 0.93 | 0.97 | 0.98 |
| Back | 1 | 0.82 | 0.90 | 0.95 | 0.98 | 0.99 |
| Back | 2 | 0.66 | 0.90 | 0.96 | 0.98 | 1.00 |
| Back | 4 | 0.44 | 0.65 | 0.84 | 0.92 | 0.96 |
| Back | 8 | 0.62 | 0.80 | 0.91 | 0.95 | 0.98 |
| Back | 16 | 0.72 | 0.84 | 0.87 | 0.94 | 0.99 |

# Appendix E

# Data

In this section, the data used to plot some of the figures included in this thesis are reported.

## E.1 Rates of growth of sensation

Table E.1: Median rate of growth of sensation, $n$, and inter-quartile ranges for fore-and-aft, lateral and vertical sinusoidal vibration in the frequency range 0.5 to 16 Hz (Figure 4.5).

| Freq. (Hz) | $n_x$ | | | $n_y$ | | | $n_z$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | 25th | Med. | 75th | 25th | Med. | 75th | 25th | Med. | 75th |
| 0.50 | 0.641 | 0.944 | 1.203 | 0.493 | 0.602 | 0.946 | 1.182 | 1.458 | 2.027 |
| 0.63 | 0.523 | 0.727 | 0.961 | 0.414 | 0.577 | 0.883 | 0.858 | 1.462 | 2.076 |
| 0.80 | 0.630 | 0.820 | 1.303 | 0.447 | 0.655 | 0.857 | 1.125 | 1.520 | 1.827 |
| 1.00 | 0.742 | 0.908 | 1.061 | 0.529 | 0.785 | 0.822 | 0.734 | 1.170 | 1.536 |
| 1.25 | 0.546 | 0.823 | 0.938 | 0.553 | 0.715 | 0.848 | 0.912 | 1.196 | 1.981 |
| 1.60 | 0.653 | 0.696 | 1.157 | 0.591 | 0.701 | 0.786 | 0.662 | 0.973 | 1.398 |
| 2.00 | 0.494 | 0.664 | 1.169 | 0.474 | 0.649 | 0.852 | 0.656 | 1.121 | 1.677 |
| 2.50 | 0.529 | 0.669 | 0.835 | 0.341 | 0.514 | 0.668 | 0.506 | 0.789 | 1.365 |
| 3.15 | 0.355 | 0.679 | 0.958 | 0.426 | 0.606 | 0.737 | 0.690 | 0.912 | 1.379 |
| 4.00 | 0.551 | 0.654 | 0.898 | 0.384 | 0.578 | 1.084 | 0.586 | 0.833 | 0.990 |
| 5.00 | 0.395 | 0.469 | 0.649 | 0.501 | 0.677 | 1.158 | 0.447 | 0.546 | 0.856 |
| 6.30 | 0.474 | 0.569 | 0.741 | 0.420 | 0.476 | 0.687 | 0.338 | 0.414 | 0.590 |
| 8.00 | 0.338 | 0.514 | 0.660 | 0.391 | 0.534 | 0.627 | 0.232 | 0.610 | 0.768 |
| 10.00 | 0.453 | 0.580 | 0.863 | 0.382 | 0.530 | 0.784 | 0.435 | 0.559 | 0.713 |
| 12.50 | 0.569 | 0.689 | 0.930 | 0.473 | 0.569 | 0.771 | 0.402 | 0.636 | 0.910 |
| 16.00 | 0.616 | 0.856 | 0.996 | 0.585 | 0.668 | 1.022 | 0.305 | 0.485 | 0.741 |

## E.2 Equivalent sensation contours

Table E.2: Median equivalent sensation contours for fore-and-aft, lateral and vertical directions. The contours for horizontal vibration correspond to magnitude estimates of 100, 130 and 160; the contours for vertical vibration correspond to magnitude estimates of 120, 150 and 180 (Figure 4.6).

| Frequency (Hz) | Fore-and-aft | | | Lateral | | | Vertical | | |
|---|---|---|---|---|---|---|---|---|---|
| | 100 | 130 | 160 | 100 | 130 | 160 | 120 | 150 | 180 |
| 0.50 | 0.096 | 0.122 | 0.153 | 0.097 | 0.133 | 0.169 | 0.529 | 0.597 | 0.671 |
| 0.63 | 0.123 | 0.169 | 0.212 | 0.123 | 0.187 | 0.256 | 0.565 | 0.656 | 0.843 |
| 0.80 | 0.170 | 0.221 | 0.267 | 0.151 | 0.220 | 0.300 | 0.732 | 0.841 | 0.934 |
| 1.00 | 0.182 | 0.260 | 0.343 | 0.194 | 0.273 | 0.356 | 0.732 | 0.876 | 0.999 |
| 1.25 | 0.250 | 0.320 | 0.428 | 0.241 | 0.356 | 0.476 | 0.818 | 0.977 | 1.116 |
| 1.60 | 0.291 | 0.400 | 0.511 | 0.275 | 0.394 | 0.507 | 0.788 | 1.159 | 1.385 |
| 2.00 | 0.325 | 0.472 | 0.606 | 0.343 | 0.501 | 0.698 | 0.833 | 1.014 | 1.252 |
| 2.50 | 0.367 | 0.555 | 0.754 | 0.372 | 0.620 | 1.069 | 0.774 | 1.040 | 1.328 |
| 3.15 | 0.398 | 0.600 | 0.860 | 0.362 | 0.732 | 0.914 | 0.691 | 0.902 | 1.044 |
| 4.00 | 0.440 | 0.650 | 0.865 | 0.564 | 0.795 | 1.014 | 0.506 | 0.676 | 0.929 |
| 5.00 | 0.379 | 0.629 | 0.963 | 0.642 | 0.929 | 1.092 | 0.346 | 0.577 | 0.756 |
| 6.30 | 0.532 | 0.831 | 1.184 | 0.450 | 0.736 | 1.162 | 0.238 | 0.440 | 0.658 |
| 8.00 | 0.649 | 1.035 | 1.509 | 0.372 | 0.687 | 1.133 | 0.283 | 0.475 | 0.704 |
| 10.00 | 0.573 | 0.962 | 1.401 | 0.393 | 0.668 | 1.143 | 0.310 | 0.551 | 0.765 |
| 12.50 | 0.694 | 1.079 | 1.521 | 0.469 | 0.860 | 1.298 | 0.277 | 0.521 | 0.728 |
| 16.00 | 0.743 | 1.037 | 1.238 | 0.577 | 0.851 | 1.227 | 0.259 | 0.398 | 0.624 |

## E.3 Main causes of discomfort

Table E.3: Main cause of discomfort for subjects exposed to fore-and-aft vibration (percentage of subjects reporting each particular factor as the main cause of discomfort, Figure 4.11).

| Frequency (Hz) | Magnitude 3 | | | Magnitude 7 | | |
|---|---|---|---|---|---|---|
| | Balance | Upper body | Legs and feet | Balance | Upper body | Legs and feet |
| 0.50 | 31.3% | 31.3% | 37.5% | 62.5% | 25.0% | 12.5% |
| 0.63 | 53.3% | 26.7% | 20% | 56.3% | 12.5% | 31.3% |
| 0.80 | 25.0% | 18.8% | 56.3% | 62.5% | 12.5% | 25.0% |
| 1.00 | 26.7% | 20.0% | 53.3% | 18.8% | 18.8% | 62.5% |
| 1.25 | 13.3% | 26.7% | 60.0% | 31.3% | 25.0% | 43.8% |
| 1.60 | 6.7% | 40.0% | 53.3% | 25.0% | 31.3% | 43.8% |
| 2.00 | 13.3% | 26.7% | 60.0% | 25.0% | 31.3% | 43.8% |
| 2.50 | 6.7% | 26.7% | 66.7% | 6.3% | 18.8% | 75.0% |
| 3.15 | 6.7% | 13.3% | 80.0% | 12.5% | 25.0% | 62.5% |
| 4.00 | 0% | 20.0% | 80.0% | 6.3% | 25.0% | 68.8% |
| 5.00 | 0% | 20.0% | 80.0% | 0% | 12.5% | 87.5% |
| 6.30 | 0% | 12.5% | 87.5% | 0% | 25.0% | 75.0% |
| 8.00 | 0% | 25.0% | 75.0% | 0% | 56.3% | 43.8% |
| 10.00 | 0% | 25.0% | 75.0% | 0% | 13.3% | 86.7% |
| 12.50 | 0% | 6.3% | 93.8% | 0% | 6.3% | 93.8% |
| 16.00 | 0% | 6.7% | 93.3% | 0% | 6.3% | 93.8% |

Table E.4: Main cause of discomfort for subjects exposed to lateral vibration (percentage of subjects reporting each particular factor as the main cause of discomfort, Figure 4.11).

| | Magnitude 3 | | | Magnitude 7 | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | Balance | Upper body | Legs and feet | Balance | Upper body | Legs and feet |
| 0.50 | 21.4% | 42.9% | 35.7% | 43.8% | 25.0% | 31.3% |
| 0.63 | 13.3% | 46.7% | 40.0% | 43.8% | 31.3% | 25.0% |
| 0.80 | 7.1% | 57.1% | 35.7% | 25.0% | 31.3% | 43.8% |
| 1.00 | 13.3% | 40.0% | 46.7% | 12.5% | 25% | 62.5% |
| 1.25 | 6.7% | 33.3% | 60.0% | 26.7% | 26.7% | 46.7% |
| 1.60 | 13.3% | 26.7% | 60.0% | 12.5% | 25% | 62.5% |
| 2.00 | 0% | 60.0% | 40.0% | 6.3% | 37.5% | 56.3% |
| 2.50 | 13.3% | 26.7% | 60.0% | 6.7% | 26.7% | 66.7% |
| 3.15 | 0% | 46.7% | 53.3% | 0% | 40.0% | 60.0% |
| 4.00 | 0% | 21.4% | 78.6% | 0% | 40.0% | 60.0% |
| 5.00 | 0% | 18.8% | 81.3% | 0% | 25.0% | 75.0% |
| 6.30 | 0% | 18.8% | 81.3% | 0% | 37.5% | 62.5% |
| 8.00 | 0% | 31.3% | 68.8% | 0% | 13.3% | 86.7% |
| 10.00 | 0% | 13.3% | 86.7% | 0% | 18.8% | 81.3% |
| 12.50 | 0% | 6.3% | 93.8% | 0% | 18.8% | 81.3% |
| 16.00 | 0% | 0% | 100% | 0% | 5.6% | 94.4% |

Table E.5: Main cause of discomfort for subjects exposed to vertical vibration (percentage of subjects reporting each particular factor as the main cause of discomfort, Figure 4.11).

| | Magnitude 3 | | | Magnitude 7 | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | Balance | Upper body | Legs and feet | Balance | Upper body | Legs and feet |
| 0.50 | 66.7% | 6.7% | 26.7% | 53.3% | 33.3% | 13.3% |
| 0.63 | 53.3% | 33.3% | 13.3% | 62.5% | 25.0% | 12.5% |
| 0.80 | 42.9% | 35.7% | 21.4% | 37.5% | 43.8% | 18.8% |
| 1.00 | 43.8% | 37.5% | 18.8% | 23.5% | 35.3% | 41.2% |
| 1.25 | 40.0% | 33.3% | 26.7% | 25.0% | 31.3% | 43.8% |
| 1.60 | 33.3% | 26.7% | 40.0% | 25.0% | 37.5% | 37.5% |
| 2.00 | 14.3% | 50.0% | 35.7% | 6.7% | 53.3% | 40.0% |
| 2.50 | 31.3% | 25.0% | 43.8% | 13.3% | 53.3% | 33.3% |
| 3.15 | 5.9% | 41.2% | 52.9% | 0% | 62.5% | 37.5% |
| 4.00 | 5.9% | 64.7% | 29.4% | 0% | 62.5% | 37.5% |
| 5.00 | 0% | 62.5% | 37.5% | 0% | 76.5% | 23.5% |
| 6.30 | 5.9% | 70.6% | 23.5% | 0% | 76.5% | 23.5% |
| 8.00 | 0% | 81.3% | 18.8% | 0% | 64.7% | 35.3% |
| 10.00 | 6.3% | 62.5% | 31.3% | 0% | 68.8% | 31.3% |
| 12.50 | 0% | 66.7% | 33.3% | 0% | 64.7% | 35.3% |
| 16.00 | 0% | 68.8% | 31.3% | 0% | 66.7% | 33.3% |

## E.4 Experimental frequency weightings

Table E.6: Experimental frequency weighting derived from the equivalent comfort contours for fore-and-aft, lateral and vertical vibration (Figure 5.3).

| Frequency (Hz) | Acceleration weighting | | |
|---|---|---|---|
| | Fore-and-aft | Lateral | Vertical |
| 0.50 | 2.079 | 1.617 | 0.861 |
| 0.63 | 1.491 | 1.155 | 0.777 |
| 0.80 | 1.134 | 0.987 | 0.609 |
| 1.00 | 0.966 | 0.798 | 0.588 |
| 1.25 | 0.777 | 0.609 | 0.525 |
| 1.60 | 0.630 | 0.546 | 0.441 |
| 2.00 | 0.525 | 0.441 | 0.504 |
| 2.50 | 0.462 | 0.357 | 0.483 |
| 3.15 | 0.420 | 0.294 | 0.567 |
| 4.00 | 0.378 | 0.273 | 0.756 |
| 5.00 | 0.399 | 0.231 | 0.882 |
| 6.30 | 0.294 | 0.294 | 1.155 |
| 8.00 | 0.252 | 0.315 | 1.071 |
| 10.00 | 0.252 | 0.315 | 0.924 |
| 12.50 | 0.231 | 0.252 | 0.966 |
| 16.00 | 0.252 | 0.252 | 1.281 |

## E.5 Support weightings

Table E.7: Median support weightings representing the effect of a bar, a shoulder support and a back support on the discomfort caused by fore-and-aft and lateral vibration (Figure 6.6).

| Frequency (Hz) | Fore-and-aft | | | Lateral | | |
|---|---|---|---|---|---|---|
| | Bar | Shoulder | Back | Bar | Shoulder | Back |
| 0.5 | 0.94 | 1.09 | 0.92 | 1.06 | 0.77 | 0.96 |
| 1.0 | 0.96 | 1.20 | 0.97 | 0.98 | 1.43 | 1.56 |
| 2.0 | 1.08 | 1.44 | 1.54 | 1.04 | 3.24 | 2.28 |
| 4.0 | 1.20 | 1.20 | 2.57 | 0.99 | 2.11 | 1.40 |
| 8.0 | 1.32 | 1.13 | 2.98 | 0.99 | 1.82 | 0.86 |
| 16.0 | 1.15 | 1.06 | 2.96 | 1.28 | 2.73 | 1.36 |

## E.6 Comparison of contours obtained in Chapters 4 and 6

Table E.8: Comparison of equivalent comfort contours obtained in Chapters 4 and 6. The contours correspond to a magnitude estimate of 130 in Chapter 4 and 80 in Chapter 6 (Figures 6.8 and 9.16).

| Frequency | Fore-and-aft | | Lateral | |
|---|---|---|---|---|
| (Hz) | Chapter 6 | Chapter 4 | Chapter 6 | Chapter 4 |
| 0.50 | 0.201 | 0.131 | 0.230 | 0.141 |
| 0.63 | | 0.182 | | 0.212 |
| 0.80 | | 0.238 | | 0.239 |
| 1.00 | 0.361 | 0.292 | 0.376 | 0.300 |
| 1.25 | | 0.353 | | 0.392 |
| 1.60 | | 0.435 | | 0.426 |
| 2.00 | 0.557 | 0.503 | 0.644 | 0.567 |
| 2.50 | | 0.619 | | 0.772 |
| 3.15 | | 0.692 | | 0.781 |
| 4.00 | 0.691 | 0.736 | 0.849 | 0.858 |
| 5.00 | | 0.741 | | 0.975 |
| 6.30 | | 0.927 | | 0.867 |
| 8.00 | 0.956 | 1.236 | 0.773 | 0.805 |
| 10.00 | | 1.092 | | 0.841 |
| 12.50 | | 1.227 | | 0.996 |
| 16.00 | 1.204 | 1.104 | 1.169 | 0.953 |

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