UNIVERSITY OF SOUTHAMPTON

EFFECT OF VIBRATION EXPOSURE DURATION ON DISCOMFORT

CEDRIC GALLAIS

DOCTOR OF PHILOSOPHY

FACULTY OF ENGINEERING SCIENCE AND MATHEMATICS

INSTITUTE OF SOUND AND VIBRATION RESEARCH

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ABSTRACT

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by Cedric Gallais

The comfort of a seated person exposed to vibration is known to depend on the magnitude, frequency content, and direction of the excitation. A review of the literature showed that very little is known about the effects of the duration of exposure to vibration on comfort.

This thesis investigates the effects of body support, frequency, waveform, and direction of excitation on the Subjective Discomfort Time-Dependency (SDTD) during vibration so as to improve understanding of the mechanisms involved (e.g. the biodynamic responses of the body and muscle activity) and elaborate a model predicting how discomfort evolves with exposure duration. To achieve these objectives, a new method of measuring the discomfort time-dependency was developed and tested.

The Subjective Discomfort Time-Dependency has been investigated in 27 experimental sessions, each with twelve subjects seated on a conventional car seat. In each session, subjects were exposed to one stimulus. The new developed method requires the subjects to adjust the magnitude of the vibration in order to keep constant their discomfort. The SDTD was obtained by measuring the platform acceleration over the exposure duration. At specific time-intervals, subjects were also asked to indicate the locations of their discomfort and provide discomfort ratings for these locations. Results showed that the amount of vibration to achieve a constant level of discomfort decreased over time (mainly during the first 15 minutes of exposure). This implies that the sensitivity of vibration increases with duration. Fore-and-aft excitations generated a greater SDTD for most stimuli. For 1-Hz lateral sinusoidal motion, the sensitivity of vibration increased at a greater rate with a harness than without. Stimuli at 1 Hz produced SDTD that were less dependent on the duration of exposure than stimuli at higher frequencies. The waveforms of the vibration had little effect on the SDTD. The discomfort rating showed that prolonged exposure to vibration produced discomfort mainly at the neck.

Because discomfort was mainly felt at the neck and that the SDTD depended on the frequency, it was hypothesised that the type of neck muscle activity produced during exposure to vibration depends on the frequency. Neck muscle activity was measured with 12 seated subjects during 10 minutes of fore-and-aft sinusoidal vibration. The r.m.s. magnitudes of the raw EMG and of the phasic and tonic components of the EMG were calculated (it was assumed that phasic muscle activity arose from the periodic vibration whereas the tonic muscle activity was needed to respond to a static load). Results showed that the frequency of vibration had no effect on the EMG r.m.s values but affected the phasic and tonic components of the EMG. Phasic activity was greatest at 1 Hz and decreased as the frequency increased. Tonic activity showed the opposite tendency. As for the SDTD studies, the frequency of excitation seems to have an effect on the phasic and tonic components of the neck muscle activity.

Phasic and tonic neck muscle activities represent different types of head motions. Because the content of phasic and tonic activities of the EMG signal seems to be linked with the effects of vibration exposure duration on discomfort, it was hypothesised that predicting the head motions may help estimating the comfort time-dependency. A three degree-of-freedom lumped parameter model was developed to predict floor-to-head transmissibility. The model was then calibrated to estimate the head motions using the floor-to-head, seat-to-head, and seat transmissibility measured with 12 subjects, exposed to fore-and-aft sinusoidal, narrow-band random, and broad-band random vibration. Results showed that the model can estimate the head motions around the frequencies of resonances (mode shapes), but requires improvement to be accurate at the other frequencies. The estimated mode shapes showed three types of head motions: at 1.4 Hz the head and neck moved in phase; at 3.5 Hz, there was a resonance of the backrest and the head and neck moved in phase, but with a greater head motion than neck motion; and at 6.9 Hz the head and neck moved out of phase.

The subjective, physiological, and biodynamic studies suggest that the SDTD increases when the neck muscles attempt to control head motions by producing greater tonic, and less phasic, activity. The lumped parameter model identified through the mode shapes three types of head motions corresponding to different comfort time-dependencies. It was hypothesized that the phase and modulus of the seat-to-head transmissibility may indicate the amount of phasic and tonic activity produced. Through neck muscle activity, a model predicting seat-to-head transmissibility may also predict the time-dependency of discomfort.

This thesis proposes a new method for determining the time-dependency of discomfort caused by whole-body vibration. Discomfort time-dependencies have been shown to depend on the frequency of vibration, direction of excitation, and body support. Mechanisms responsible for the discomfort time-dependency have been proposed.

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1 INTRODUCTION

1.1 GENERAL INTRODUCTION

The human body is exposed to vibration, while travelling, working or even while staying at home. Vibration has different effects on the human body. Vibration transmitted to the body can affect health, performance and also the perceived comfort (Griffin, 1990).

As the expectation of the quality of live has risen, comfort has become a critical commercial target. In the second half of the last century, the automotive industry sponsored much of the research on comfort. The effects of vibration magnitude, frequency and direction on comfort are well documented for seated subjects. Standards propose procedures and tools to measure and evaluate the effects of whole-body vibration on comfort (BS 6841, 1987; ISO 2631, 1997). Frequency-weighting curves take into account the effects frequency and direction of the vibration, multiplying factors consider the influence of the locations of the input vibration (i.e., feet, seat-pan, and backrest).

Although the literature provides a rich source of information concerning the response of the human body to the magnitude, frequency and direction of vibration, there are few studies investigating the effects of vibration duration on comfort.

The research described in this thesis was conducted to improve understanding of the effects of the duration of vibration exposure on discomfort.

1.2 DEFINITION OF TERMS

The purpose of this Section is to define all the main variables referred to in this thesis.

1.2.1 Definition of the variables linked with discomfort

Comfort is defined in dictionaries as “a state of physical ease or well-being” or “a relief from suffering or grief”. Discomfort can be defined as a “mental and bodily distress” or “a mild pain”. In the context of human response to whole-body vibration, the standard BS ISO 5805 (1997), defines comfort as a “(biodynamics) subjective state of well-being or absence of mechanical disturbance in relation to the induced environment (mechanical vibration or repetitive shock)”. “The study of the relation between vibration and comfort has mainly concerned the extents to which motions are responsible for displeasure, dissatisfaction and discomfort” (Griffin, 1990).

Helander and Zhang (1997) suggested that comfort is not only the absence of discomfort. They suggested that comfort and discomfort are not the extremities of a one dimension scale but that comfort and discomfort exist at the same time and constitute a two dimensional scale. From the general definitions of comfort and discomfort presented in the previous paragraph, exposure to vibration is likely to affect “discomfort” rather than “comfort”. “Vibration discomfort” may be used for the feelings generated by the exposure to vibration. This thesis deals with vibration discomfort which is assumed to be distributed along a uni-polar scale from no discomfort to maximum discomfort. In this thesis, three variables linked with vibration discomfort were evaluated: global level of discomfort, location of discomfort and discomfort rating. The subjective discomfort time-dependency (SDTD) will be used to describe the relationship between discomfort and duration; it shows how discomfort varies over time.

Global level of discomfort:

The global level of discomfort can be defined as the general feeling of disturbance, at an instant *t*. During the subjective trials, subjects were asked to keep constant their global level of discomfort by adjusting the level of vibration (see Chapter 3, Section 3.4). The global level of discomfort is a short term or instantaneous integration of all types of discomfort experienced at an instant *t*.

Location of discomfort:

The location of discomfort can be defined as a body part where a feeling of discomfort is experienced, irrespective of whether it is caused by exposure to whole-body vibration or prolonged static pressure from sitting down.

Rating of discomfort:

The rating of discomfort can be defined as the level of discomfort at a specific body location. During the subjective trials, subjects were asked, every five or ten minutes, to identify body locations where discomfort was experienced and give a rating of this discomfort using a standardized uni-polar scale (BS 6841, 1987) from 0 to 5: 0 being not uncomfortable and 5 being extremely uncomfortable.

Subjective Discomfort Time-Dependency (SDTD):

The subjective discomfort time-dependency (STDT) is defined as the change of sensitivity to the vibration magnitude over time. Subjects were asked to keep constant their global level of discomfort by adjusting the level of the vibration amplitude. A long-term reduction in the vibration amplitude was interpreted as meaning the vibration had increased their sensitivity to the vibration magnitude, and vice-versa. Therefore, by measuring the magnitude of the acceleration to which they were exposed during the entire duration of the experiment, the experimenter had access to the changes of acceleration made by the subjects and was able to deduce the subjective discomfort time-dependency (see Chapter

3, Section 3.4). The SDTD produced by various stimuli will be compared. A stimulus ‘A’ that produces a greater SDTD than a stimulus ‘B’, means that the measured acceleration magnitude decreases with exposure duration at a faster rate when subjects are exposed to the stimulus ‘A’ than when they are exposed to the stimulus ‘B’.

1.2.2 Definition of the variables linked with muscle activity

Because it was believed that it might help to explain the subjective results obtained, neck muscle activity measurements were carried out on subjects exposed to whole-body vibration. From the raw data acquired, different variables have been calculated.

EMG neck muscle activity:

EMG neck muscle activity is the electromyographic signal produced by the contraction of the neck muscle fibers. Three electrodes allow acquiring the electrical potential representative of the neck muscle response to the exposure of whole-body vibration.

Localized muscle fatigue:

Localized muscle fatigue represents a change of the muscle response over time caused by a repetitive or prolonged exposure to an external stimulus. Muscle fatigue is observed when the r.m.s. value of the EMG activity increases and the median frequency decreases (see Chapter 5, Section 5.2.2.3)

Phasic neck muscle activity:

The phasic activity represents the periodic part of the muscle activity that responds to the excitation. It represents the periodic contraction of the muscle fibres required to respond to the exposure of whole-body vibration.

Tonic neck muscle activity:

The tonic activity represents the muscle activity needed to respond to a static load. It represents a continuous, almost permanent contraction of the muscle fibres needed to respond to the exposure to whole-body vibration.

1.2.3 Definition of the variables linked with biodynamics

Biodynamic measurements were conducted to better understand the subjective results obtained and to propose a model capable of estimating the subjective discomfort time-dependency. Acceleration has been measured at the head, on the seat and on the platform in order to calculate the biodynamic responses of the seat and the body, and test for any relationship with subjective discomfort time-dependency.

Seat transmissibility:

Seat transmissibility represents the dynamic properties of the seat. It shows how vibrations are transmitted from the vibrator platform to the seated body, which type of vibration is amplified, and which type of vibration is attenuated.

Seat to head transmissibility:

Seat to head transmissibility represents the dynamic response of the seated body to an excitation localized at the seat/person interfaces (seat-pan and backrest). It shows how vibrations could be transmitted from the seat to the head.

Mode shapes:

The mode shapes are constituted of the eigen values and the eigen vectors of a system. The eigen vectors can describe how the different rigid bodies that constitutes the system move relative to each other. The eigen values represent the frequencies at which resonances occur.

1.3 OBJECTIVES OF THE RESEARCH

The research has three main objectives:

- To elaborate a new method suitable to measure and compare subjective discomfort time-dependencies (SDTD) produced by various vibratory stimuli.
- To investigate the effects of different vibration characteristics (frequency, waveform and direction) and body support on the SDTD.
- To improve understanding of the mechanisms involved in the evolution of discomfort during prolonged exposure to vibration and to develop a model estimating the SDTD.

1.4 HYPOTHESES OF THE RESEARCH

With the shortage of studies investigating the effects of vibration frequency, waveform, magnitude and direction of excitation on the subjective discomfort time-dependency it could not be stated clearly how vibration characteristics affect the evolution of discomfort with exposure duration.

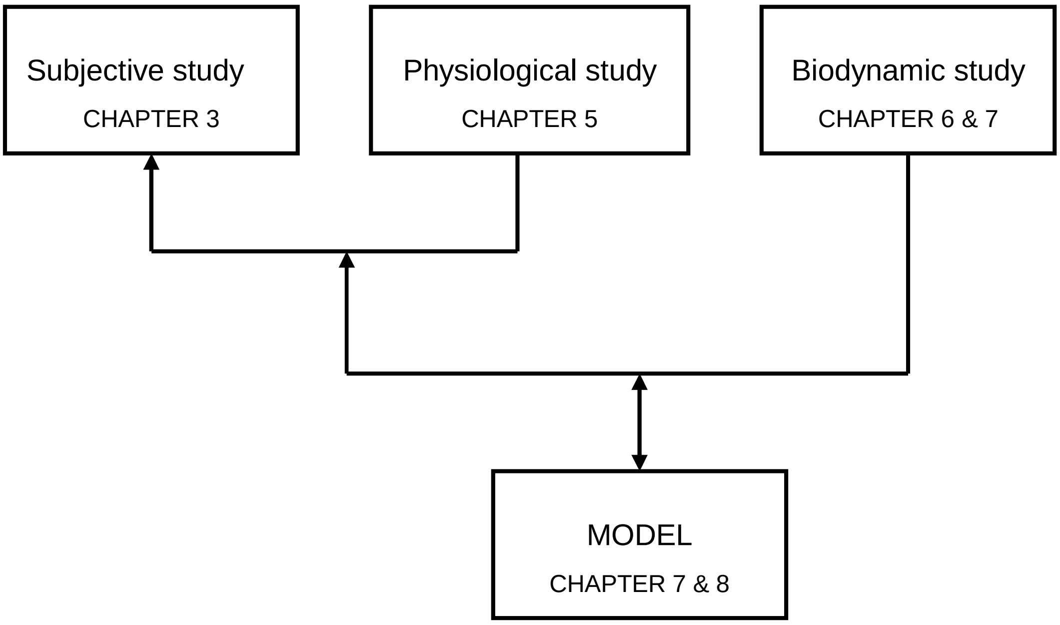


Figure 1.1 Milestones of the research

It was assumed that vibrations producing different body motions could generate different comfort time dependencies.

From this statement it was hypothesized that:

- Discomfort increases with increasing duration of vibration exposure.
- Discomfort increases at different rates depending on the vibration characteristics (frequency, waveform, direction, magnitude).
- Body support affects the rate of increase in discomfort with exposure duration.
- Discomfort is felt at different locations in the body depending on the vibration characteristics (frequency, waveform, direction). Moreover, the location of discomfort changes during the exposure duration.

These were the starting hypotheses that were investigated in the first part of the thesis. As the understanding of the mechanisms of the evolution of discomfort with duration improved, more specific hypotheses were formulated and tested in later parts of the thesis.

1.5 MILESTONES OF THE RESEARCH

This research is composed in three main studies: subjective, physiological and biodynamic. Figure 1.1 illustrates how the relationships between these three studies were investigated and led to a model predicting the subjective discomfort time dependency (SDTD).

The subjective study, which investigated the effects of different vibration characteristics (frequency, waveform and direction) and body support on the SDTD, suggested that neck muscle activity may be involved in the mechanisms responsible of the evolution of discomfort with exposure duration.

The physiological study investigated the effect of vibration frequency on neck muscle activity. The relationship between the subjective results and the physiological results suggested that head motions controlled by phasic neck muscle activity (muscle activity arising as a result of periodic vibration) may produce less SDTD that head motions controlled by tonic neck muscle activity (muscle activity needed to respond to a static load). It was then hypothesised that the types of head motion producing SDTD may be estimated from the backrest-to-head transmissibility and the predicted mode shapes obtained from a lumped parameter model.

The biodynamic study consisted of measuring the vibration transmission from the input vibration at the floor to the seat and to the head. The backrest-to-head transmissibility was measured to investigate the relationship between head motion and the neck muscle activity produced. The floor-to-head transmissibility and seat transmissibility were measured for modelling purposes. A three degree-of-freedom lumped parameter model representing the head, neck and upper-back was developed and optimised using the measured floor-to-head transmissibility. From these results a model predicting the SDTD was developed.

1.6 STRUCTURE OF THE RESEARCH

The thesis is composed of nine chapters including this Chapter 1:

CHAPTER 2 LITERATURE REVIEW

This chapter reviews the literature dealing with the effects of vibration exposure duration on discomfort. Different comfort time-dependencies are presented. The methods used to measure the effects of vibration duration on discomfort are listed. When available, the effects of vibration characteristics and body supports on the SDTD are described.

CHAPTER 3 SUBJECTIVE STUDY

This chapter presents a new method developed to measure and compare the discomfort time-dependencies caused by different stimuli. It investigates the effects of vibration characteristics (frequency, waveform and direction) and body support on the SDTD. Possible mechanisms responsible of the SDTD are also presented.

CHAPTER 4 SUPPORTING INFORMATION CONCERNING THE METHOD

This chapter describes the different tests conducted to give supporting information concerning the behaviour of the method.

CHAPTER 5   PHYSIOLOGICAL STUDY

This chapter investigates the effects of vibration frequency on neck muscle activity. The relationship between the subjective studies results and the physiological results is described. More detailed mechanisms possibly responsible of the SDTD are presented.

CHAPTER 6   TRANSMISSIBILITY STUDY

This chapter presents the measured floor-to-head transmissibility, seat transmissibility and backrest-to-head transmissibility. It described how the backrest-to-head transmissibility can be predicted from the floor-to-head transmissibility and the backrest transmissibility. The relationship between the backrest-to-head transmissibility (phase and modulus) and the neck muscle activity is described. A possible association between backrest-to-head transmissibility and the SDTD is hypothesised.

CHAPTER 7   HEAD AND NECK MODEL

This chapter develops a three degree-of-freedom lumped parameter model of the head and neck. The implication of this biodynamic model in a model predicting the SDTD is investigated.

CHAPTER 8   DISCUSSION

This chapter presents the advantages and the possible drawback of the new method developed to measure the discomfort time-dependency. The effects of the subjective results on the accuracy of the frequency-weighting and time-dependency curves presented in standards (ISO 2631, 1997; BS 6841, 1987) are discussed. The understanding of the mechanisms responsible of the evolution of discomfort with exposure duration, gained from the measurement of neck muscle activity, is described. Possible models for estimating the SDTD and possible hypothesis for further research are presented.

CHAPTER 9 CONCLUSION

This chapter presents the main results of each study conducted. It suggests possible further research and states the contribution to knowledge delivered by this thesis.

Table 1.1 summarizes all the experimental sessions conducted. The different subjects' environments used are described and justified in the relevant Chapters

Table 1.1 The experimental sessions conducted

Studies	Experiment	Sessions	Subject environment	Stimuli	Measurements	Page
SUBJECTIVE STUDIES	Magnitude estimation and cross modality test	Session 1	Headphone and blindfold	Lateral sinusoidal and narrow-band random vibration stimuli of duration of 10 s at 1 Hz and 4 Hz and shocks at 1 Hz with magnitude between 0.1 and 1.0 m.s-2 r.m.s. Sound stimuli of 10 s at 1000 Hz from 45 dB[A] to 85 dB[A]	Equivalent comfort contours; Reference: lateral, sinusoidal, 10 s, 4 Hz at 0.5 m.s-2 r.m.s.	53, 66
		Session 2	Cabin, headphone no blindfold	Fore-and-aft sinusoidal and narrow-band random vibration stimuli of duration of 10 s at 1 Hz and 4 Hz and shocks at 1 Hz with magnitude between 0.1 and 1.0 m.s-2 r.m.s. Sound stimuli of 10 s at 1000 Hz from 45 dB[A] to 85 dB[A]		
		Session 3	Cabin, headphone and no blindfold	Vertical sinusoidal and narrow-band random vibration stimuli of duration of 10 s at 1 Hz and 4 Hz and shocks at 1 Hz with magnitude between 0.1 and 1.0 m.s-2 r.m.s. Sound stimuli of 10 s at 1000 Hz from 45 dB[A] to 85 dB[A]		
	Lateral time-dependency	Session 1	Headphone and blindfold	60 minutes of lateral sinusoidal vibration at 4 Hz	Evolution of discomfort due to prolonged exposure to vibration	56, 71
		Session 2		60 minutes of lateral sinusoidal vibration at 1 Hz		
		Session 3		60 minutes of lateral narrow-band random vibration at 4 Hz		
		Session 4		60 minutes of lateral narrow-band random vibration at 1 Hz		
		Session 5		60 minutes of lateral shocks vibration at 1 Hz		
		Session 6	Nothing	30 minutes of lateral narrow-band random vibration at 8 Hz		
		Session 7	Nothing	30 minutes of lateral narrow-band random vibration at 16 Hz		
		Session 8	Headphone and blindfold with a 4 points harness	15 minutes of lateral sinusoidal vibration at 1 Hz		

(following Table 1.1)

Studies	Experiment	Sessions	Subjects' environment	Stimuli	Measurements	Page
SUBJECTIVE STUDIES	Fore-and-aft time-dependency	Session 1	Cabin, no headphone and no blindfold	60 minutes of fore-and-aft sinusoidal vibration at 4 Hz	Evolution of discomfort due to prolonged exposure to vibration	59, 76
		Session 2		60 minutes of fore-and-aft sinusoidal vibration at 1 Hz		
		Session 3		60 minutes of fore-and-aft narrowband random vibration at 4 Hz		
		Session 4		60 minutes of fore-and-aft narrowband random vibration at 1 Hz		
		Session 5		60 minutes of fore-and-aft shocks vibration at 1 Hz		
		Session 6	Nothing	30 minutes of fore-and-aft narrowband random vibration at 8 Hz		
		Session 7	Nothing	30 minutes of fore-and-aft narrowband random vibration at 16 Hz		
		Session 8	headphone and blindfold	15 minutes of fore-and-aft sinusoidal vibration at 0.5 Hz		
	Vertical time-dependency	Session 1	Cabin, no headphone and no blindfold	60 minutes of vertical sinusoidal vibration at 4 Hz	Evolution of discomfort due to prolonged exposure to vibration	63, 80
		Session 2		60 minutes of vertical sinusoidal vibration at 1 Hz		
		Session 3		60 minutes of vertical narrowband random vibration at 4 Hz		
		Session 4		60 minutes of vertical narrowband random vibration at 1 Hz		
		Session 5		60 minutes of vertical shocks vibration at 1 Hz		
		Session 6	Nothing	30 minutes of fore-and-aft narrowband random vibration at 8 Hz		
		Session 7	Nothing	30 minutes of fore-and-aft narrowband random vibration at 16 Hz		
	Control study	Session 1	headphone and no blindfold	60 minutes of magnitude modulated acoustic white noise **No vibration**	Evolution of discomfort due to prolonged **static posture**	65, 84

(Following Table 1.1)

Studies	Experiment	Sessions	Subjects' environment	Stimuli	Measurements	Page
ROBUSTNESS OF THE METHOD	Repeatability	Session 1 to 6	Headphone and blindfold	30 minutes of fore-and-aft sinusoidal vibration at 4 Hz	Test de repeatability of the method	103 - 115
	Alternative method	Session 1		36 minutes of 4 Hz and magnitude adjustable 1 Hz fore-and-aft sinusoidal vibration alternating every 10 s	Comparison of the results with an alternative method	
		Session 2		36 minutes of 1-Hz and magnitude adjustable 4-Hz fore-and-aft sinusoidal vibration alternating every 10 s		
PHYSIOLOGICAL STUDIES	Neck muscle activity	Session 2	No hedphone and no blindfold, SEMG electrodes placed on the neck muscles	10 minutes of fore-and-aft sinusoidal vibration at 2 Hz and 10 minutes of fore-and-aft sinusoidal vibration at 4 Hz	Measure of the neck muscle activity and calulation of phasic and tonic neck muscle activies	116 - 152
		Session 3		10 minutes of fore-and-aft sinusoidal vibration at 8 Hz and 10 minutes of fore-and-aft sinusoidal vibration at 16 Hz and 10 minute with no vibration		
BIODYNAMIC STUDIES	Transmissibility	Session 1	No headphone and no blindfold, subjects hold a "bite-bar" mounted with accelerometers with their teeh	fore-and-aft sinusoidal stimuli from 0.5 Hz to 16 Hz (in third octave); fore-and-aft narrowband random stimuli from 0.5 Hz to 16 Hz (in octave); fore-and-aft broadband random stimuli between 0.5 Hz and 16 Hz	Measure of seat and floor to head transmissibilities	153 - 185

2 LITERATURE REVIEW

2.1 INTRODUCTION

It seems that the literature dealing with the effects of vibration exposure duration on comfort has a turning point in the year 1974, corresponding to the publication of the ISO 2631 standard. Before 1974, few studies considered duration as a dependent variable (Loach, 1958; Magid *et al*., 1960; Notess and Gregory, 1963; Miwa, 1968; Simic, 1970; Miwa *et al*., 1973). The ISO 2631(1974) standard produced a "fatigue-decreased proficiency boundary". From this curve was derived an "exposure limit" and a "reduced comfort boundary". According to von Gierke (1975), this time-dependency was established with results from studies by Miwa *et al*. (1973) and Simic (1970). However the origin of the data and the way they were interpreted to form the "Fatigue-decreased proficiency" gave rise to rich discussions. In the following decade, numerous studies were performed in order to test the standard, or to propose other time-dependencies.

The relevant literature has been reviewed by Clarke (1979), Kjellberg and Wikström (1985) and Howarth (1986). These three reviews agree on one point, they do not agree with the time-dependency proposed in ISO 2631 (1974). Clarke (1979) affirmed that there is "no evidence to support the assertion of a time-dependency effect". Kjellberg and Wikström (1985) suggested that the time-dependency proposed in 1974 "constitutes an overestimation of the importance of exposure time for the strength of the effects". Howard (1986) agreed on the overestimation of the duration effect and suggested a new time-dependency (defined by Griffin and Whitham, 1980) based on the vibration dose value (VDV) or the root-mean-quad (r.m.q.), which are now accepted in British Standard 6841 (1987) and International Standard 2631 (1997). These notions are defined later in this chapter.

This review is composed of five main sections. The first section presents different time-dependencies classified according to the effects of exposure duration produced on discomfort. Then the different methods to measure the discomfort time-dependency are considered. The third section deals with the effects of vibration characteristics and posture on the discomfort time-dependency. The fourth section presents the different types of measure performed in order to understand the mechanisms of the discomfort time-dependency. The last section describes the body areas where discomfort is experienced during prolonged exposure to vibration.

It is reminded that the term SDTD refers to the subjective discomfort time-dependencies, or how discomfort evolves with vibration duration.

2.2 CLASSIFICATION OF THE PREVIOUS COMFORT TIME-DEPENDENCIES

2.2.1 Discomfort decreases with increasing vibration exposure duration

Clevenson *et al*. (1978) stated that "passengers within various transportation vehicles tend to adapt to the vibration environment imposed upon them by vehicle operations". An experiment was performed with 210 subjects exposed to simulated vibration environments. The duration ranged from 15 seconds to one hour. At the end of the pre-selected duration, the subjects were asked to make a numerical rating of the discomfort they experienced due to ride vibrations. The results of the experiments showed that discomfort decreased with increasing vibration duration (see Figure 2.1). The method and the results are commented upon in more detail in Section 2.3.3.

2.2.2 No evidence of changes of comfort with vibration exposure duration

Oborne and Clarke (1975) conducted studies on a train and on a hovercraft. Passengers were asked to rate the vibration on a discomfort scale only once during travel. The results of these experiments are presented in Figure 2.2. The rating of discomfort made by the passengers did not increase with the duration of travel. The results show great inter-subject variability. In this experiment subjects were asked to rate the discomfort they experienced after a specific duration. The study compared the subjects' ratings of

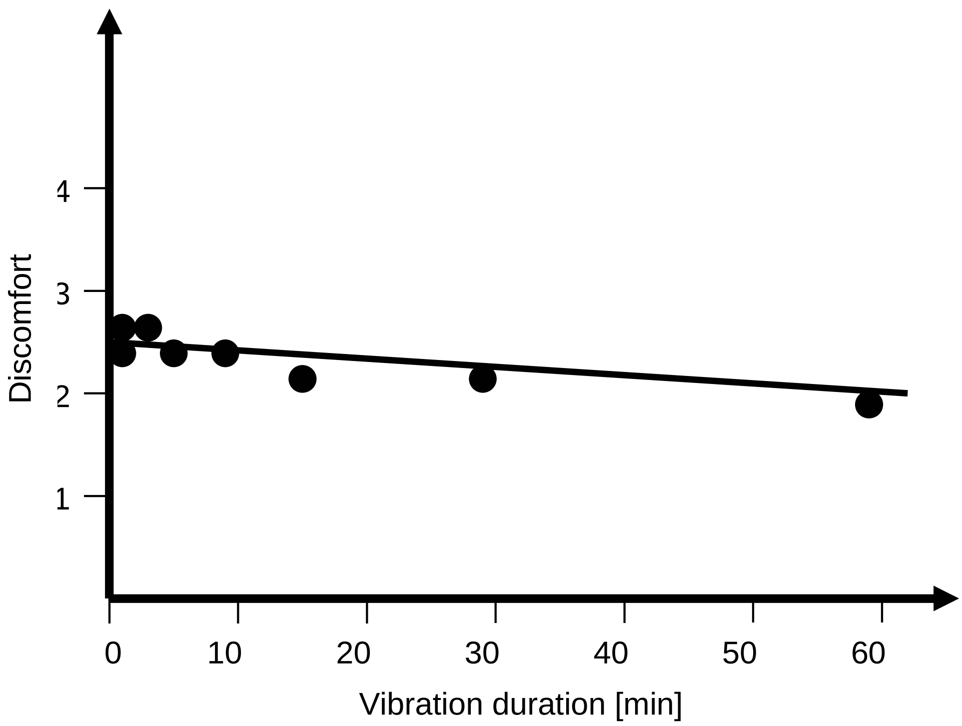


Figure 2.1 Subjective rating of discomfort, effect of vibration duration (from Clevenson *et al.,* 1978)

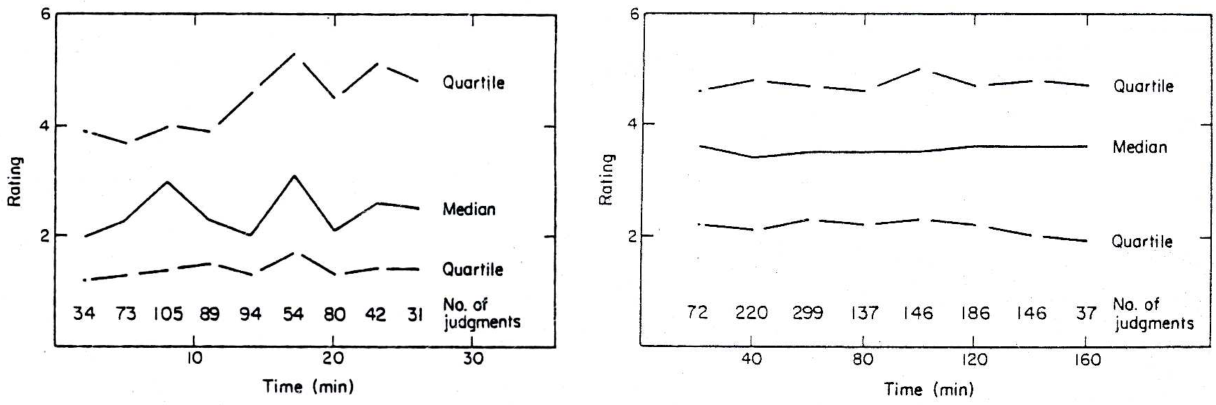


Figure 2.2 Right: Hovercraft motion rating. Left: Train vibration rating. 'No. of judgments' is the number of passengers who rated the vibration at a specific time during travel (taken from a study of Oborne and Clarke, 1975).

discomfort at different times but not the evolution of discomfort with time. From this study it seems difficult to conclude on the effect of vibration exposure duration on comfort.

In a laboratory study, Falou *et al*. (2003) measured the evolution of discomfort with duration with and without vibration exposure. Subjects were seated during 150 minutes. Total discomfort was measured using a 10-point semantic scale at the 20th, 35th, 65th, 85th, 120th 135th and 150th minute. Their results showed that discomfort increased with increasing duration at the same rate, with or without exposure to vibration (see Figure 2.3). The study failed to show any time-dependency due to vibration. Static discomfort might have masked the discomfort produced by the vibration. This result revealed the critical need to use a control condition when conducting such experiments. It seems also important to reduce static discomfort and investigate the discomfort at various parts of the body as static and dynamic discomfort might arise at different locations.

2.2.3 Discomfort increases with increasing vibration exposure duration

Loach (1958) produced curves of equal fatigue (see Figure 2.4). These time-dependencies (for lateral and vertical 1.4-Hz oscillations) are defined as "the length of time after which the average person begins to experience a clear sense of fatigue". According to Loach, these curves have been established from the experimental results of Mauzin-Sperling but no published study was found. Notess (1963) presented a time-dependency for vertical vibration at frequencies below 1 Hz (see Figure 2.5). Both figures show that acceleration magnitude decreases with increasing vibration exposure duration. Information given is too limited to know how these curves were built.

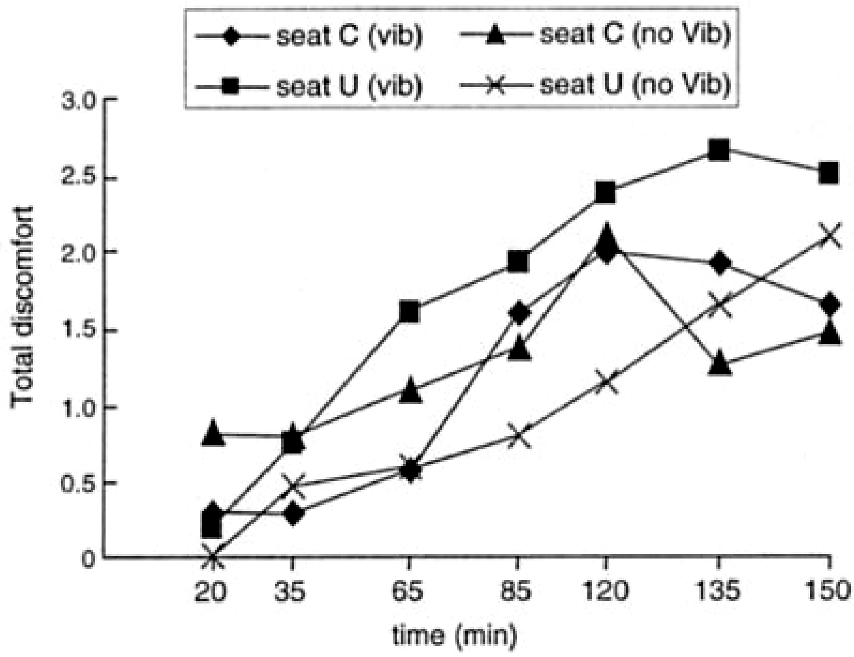


Figure 2.3 Subjective ratings of total discomfort by time period for four conditions: one comfortable seat with vibration (seat C vib) and with no vibration (seat C no vib) and a seat assumed to be uncomfortable with vibration (seat U vib) and without vibration (seat U no vib), from Falou *et al.*, 2003)

The standard ISO 2631 published in 1974 was the first to propose discomfort time-dependencies. This standard proposed the "fatigue-decreased proficiency boundary". This time-dependency is defined as a function of frequency and exposure duration. "The boundary specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks". From the fatigue-decreased proficiency boundary are derived the "exposure limit" and the "reduced comfort-boundary". The exposure limit is defined as the "maximum safe exposure" and is obtained by doubling the acceleration according to the criterion of fatigue-decreased proficiency. The reduced comfort boundary is related to difficulties of carrying out activities such as eating, reading and writing. The reduced comfort boundary is assumed to lie at approximately one-third of the corresponding acceleration levels of the fatigue-decreased proficiency. The discomfort time-dependency presented shows the same rate of increase of discomfort for all frequencies between 1.0 Hz and 80 Hz.

The references in the ISO 2631 (1974) standard cited the studies previously described (Loach, 1958; Notess, 1963) and also studies from Simic (1970) and Miwa *et al.* (1974). Von Gierke (1975), who was the chairman of the ISO committee, commented on the content of ISO 2631 (1974). He stated that the time-dependencies proposed in the standards came from compiled information (von Gierke, 1965): “short-time physiological tolerance decreased with time (observed from 20 seconds to 3 minutes); subjective judgement of intolerable exposures and working proficiency exhibited a decrease from several minutes to 2-hours exposure; subjective fatigue of railroad travellers occurred at lower vibration levels with increasing exposure time (reported for 20 minutes to 8 hours); and similarly airline passengers comfort required lower levels with increasing exposure time (up to 1 hour)”. He also stated that more recent studies (Simic, 1970 and Miwa *et al.* 1973) confirmed the time-dependencies proposed. Figure 2.6 presents the time-dependency produced in ISO 2631 (1974) and the data points taken from the results of Simic (1970) and Miwa *et al*. (1973). According to Clarke (1979), these data points do not reflect the actual results of Simic (1970) and Miwa *et al*. (1973). To appear on the time-dependency proposed in ISO 2631 (1974), the data points from Simic (1970) had to be 100% extrapolated. Concerning the data from Miwa *et al*. (1973), only a few points, assimilated to turning points (points where the time-dependency is changing suddenly), were chosen to appear on the ISO curve. But when the results from Miwa *et al*.(1973) are compared with the data points taken to build the time-dependency proposed in the ISO 2631 (1974), it does not coincide.

Experiments conducted after the publication of the ISO 2631 (1974) presented more elaborated methods that focused on establishing the effects of exposure duration on discomfort.

Maslen (1975) and Griffin (1982) proposed comparing the time dependency of ISO 2631 (1974) with various time dependencies given by $(a)^n \times t$ = constant, where a is the

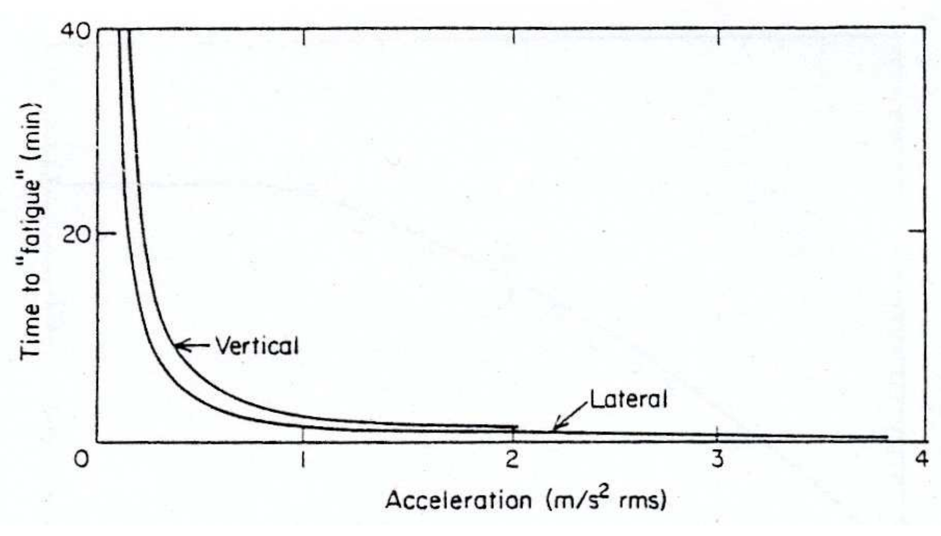


Figure 2.4 Time dependency proposed by Loach 1954 (taken from Clarke, 1979).

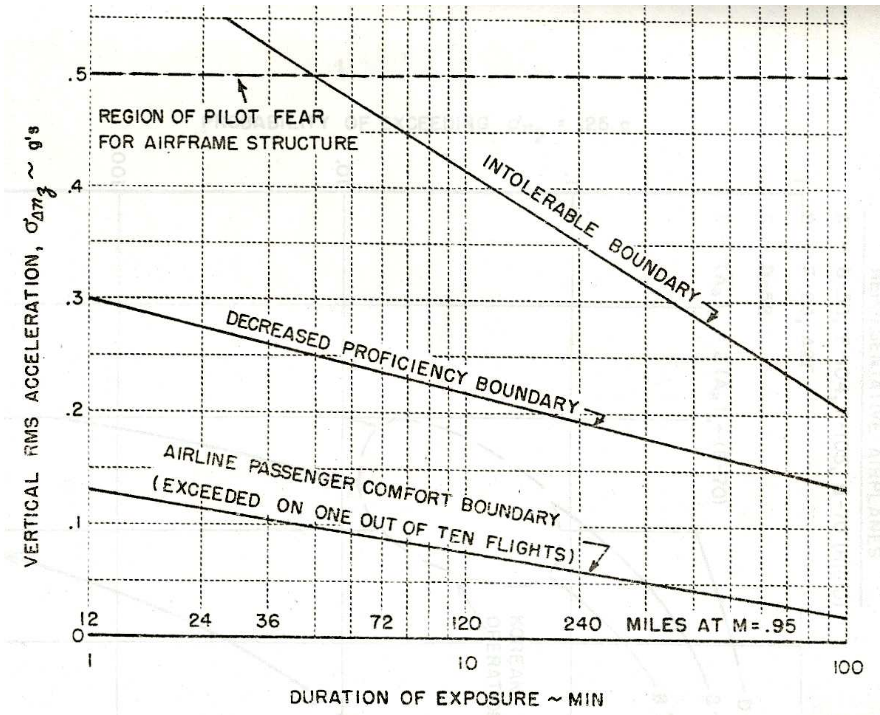


Figure 2.5 Time dependency proposed by Notess, 1963 (taken from Notess, 1963).

acceleration magnitude, *t* the duration of exposure and n = 1, 2, 3, 4 and ∞. Figure 2.7 shows that the time dependency proposed in ISO 2631 (1974) corresponds approximately, between 10 minutes and 8 hours of vibration exposure, to root-mean-square averaging, which implies a time-dependency given by $(a)^2 \times t$ = constant. This time-dependency was derived from the "conservation of energy" (Maslen, 1975). It also means that the comfort time-dependency can be represented by the root-mean-square (r.m.s.) of the acceleration defined by:

$$a._{rms} = \left(\frac{1}{T} \int_0^T a^2(t)dt \right)^{1/2}$$, with *T* the exposure duration and *a*, the acceleration.

Between 1 minute and 10 minutes, there is little effect of vibration duration on comfort in the standard. The standard does not provide a time-dependency for durations less than 1 minute.

Research on the effects of duration of vibration exposure has been performed to determine how shocks can be included in a comprehensive measure of the vibration load on man. Miwa (1968) concluded that there is a "critical time limit". The discomfort increased with increasing durations until the critical time limit is reached (2.0 seconds for 2-60 Hz and 0.8 second for 60-200 Hz). Griffin and Whitham (1980) and Kjellberg and

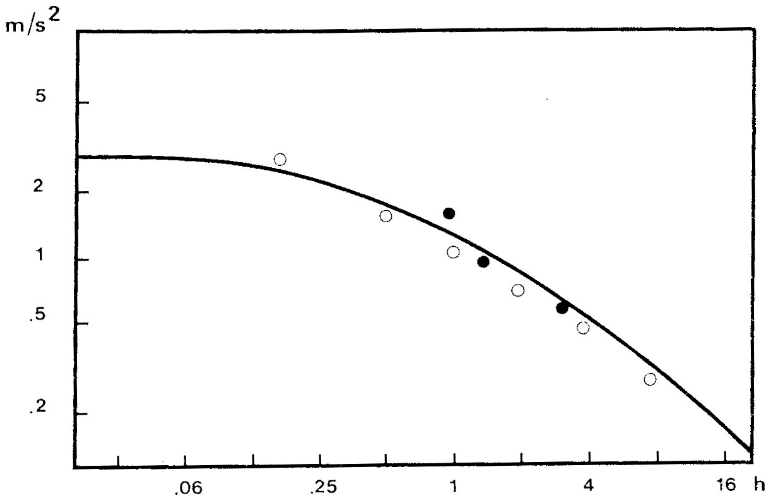


Figure 2.6 Time dependencies proposed in ISO 2631 (1974) curve: -; Miwa et al (1963): ● ; and Simic (1970):○ (taken from von Gierke, 1975).

Wikström (1984) studied the effects of shock duration on comfort. They used different methods but both found that discomfort increased with the shock duration (see Figures 2.8 and 2.9). Griffin and Whitham did not find any critical time limits. Kjellberg and Wikström found a turning point where the rate of increase of discomfort was reduced but no critical

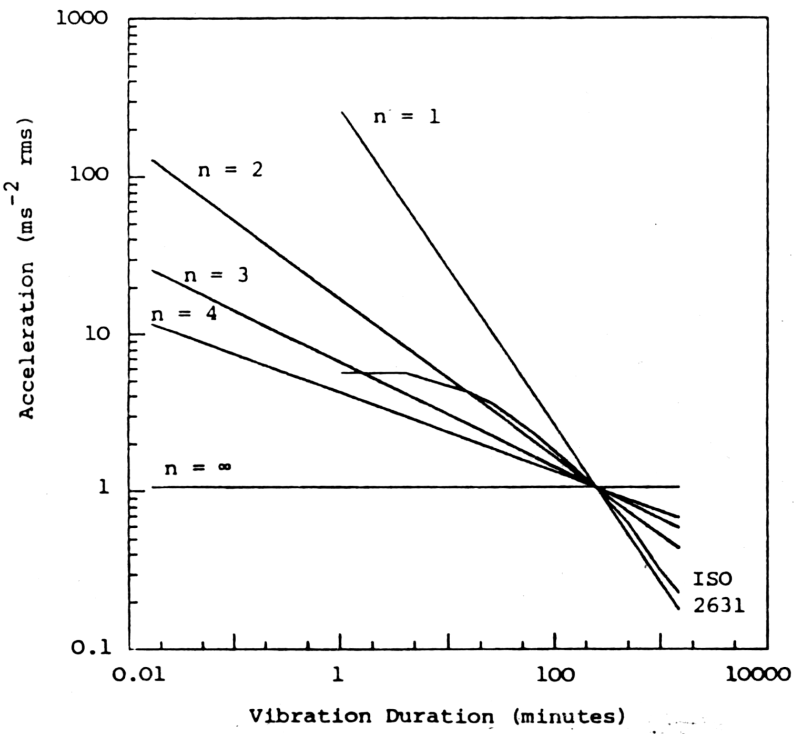


Figure 2.7 Time dependency proposed by ISO 2631 (1974) compared with time dependencies given by (a) ^{n} × t = constant, with n = 1, 2, 3, 4 and ∞ (taken from Griffin, 1982).

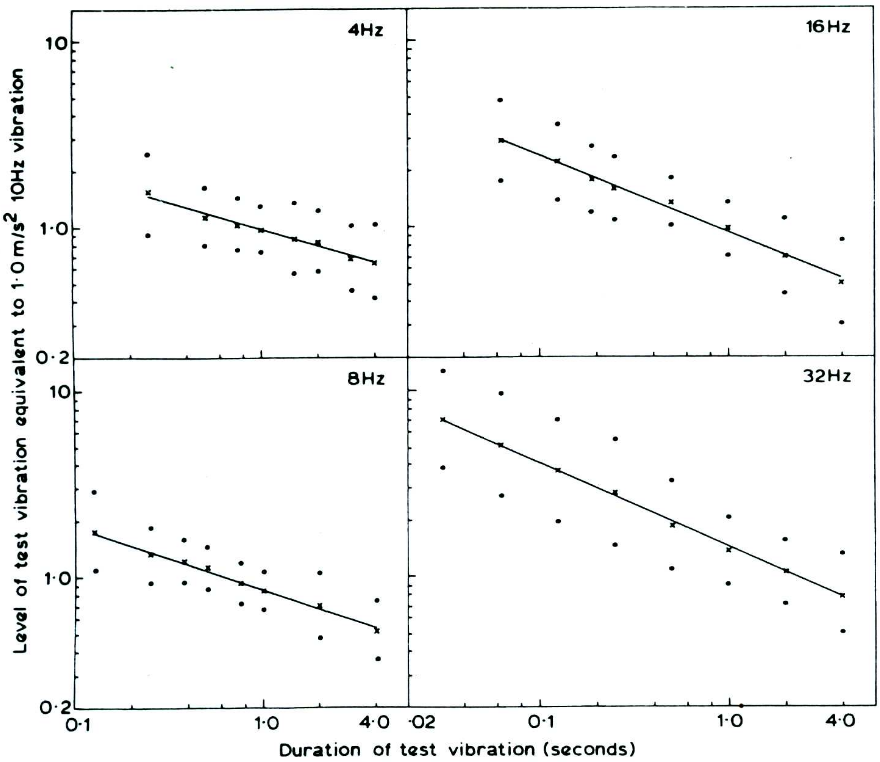


Figure 2.8 Effect of vibration duration on discomfort for vertical shocks (taken from Griffin and Whitham, 1980).

time limits were found. Both studies found that the time-dependency proposed by the standard ISO 2631 (1974), overestimated the effects of duration on comfort.

Griffin and Whitham (1980) proposed a time-dependency where motions containing high peak values can be better evaluated. The root-mean-quad of the acceleration was proposed to replace or complement the root-mean-square of the acceleration for the evaluation of sensations produced by motion containing high peak values. The root-mean-quad is defined by the relation:

$$a._{rmq} = \left(\frac{1}{T} \int_0^T a^4(t)dt \right)^{1/4}$$, with *T* the exposure duration and *a*, the acceleration

The root-mean-quad (r.m.q.) was also proposed as a time-dependency under the form: $(a)^4 \times t$ = constant.

The current standards, ISO 2631 (1997) and the BS 6841 (1987) adopted the time-dependency proposed by Griffin and Whitham (1980).

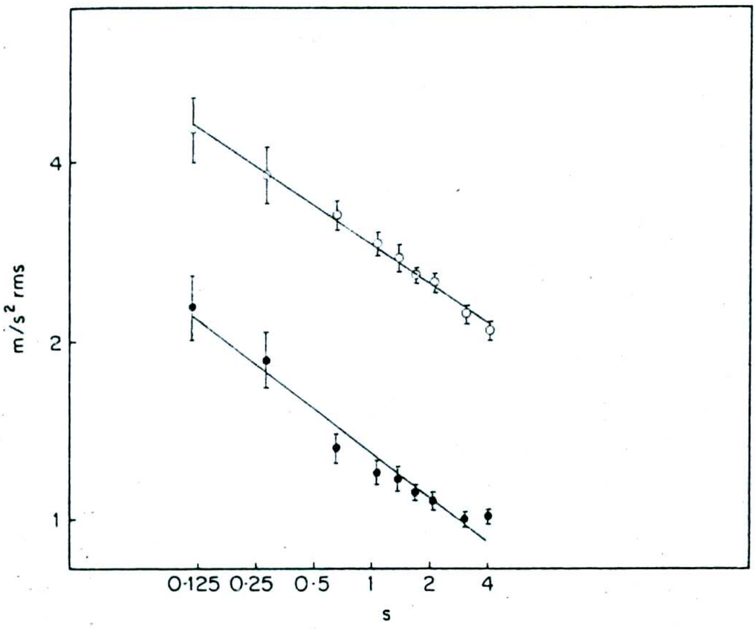


Figure 2.9 Time dependency of 31.5 Hz vertical shocks. The data correspond to the intensity and pulse duration that causes the same level of discomfort as a vibration of 3 seconds duration with 2.3 m.s^{-2} rms: ○ and 1.1 m.s^{-2} rms: ●.(taken from Kjellberg and Wikström, 1984).

International Standard 2631 (1997) contains both the "conservation of energy" equation based on the r.m.s., $(a)^2 \times t$ = constant, first provided by Maslen (1975), and also the time-dependency based on the r.m.q. defined by $(a)^4 \times t$ = constant (see Figure 2.10).

The current British Standard, BS 6841(1987), proposes a time-dependency using the vibration dose value (VDV). The VDV is generated from the r.m.q.:

$$VDV = \left(\int_0^T a^4(t)dt \right)^{1/4}$$, with T the exposure duration and a, the acceleration

The time-dependency in BS 6841 (1987) gives the r.m.s. acceleration corresponding to various dose values and exposure durations (see Figure 2.11).

2.3 METHODS TO MEASURE THE DISCOMFORT TIME-DEPENDENCY

This section reviews alternative methods of determining a discomfort time-dependency by experimental measurements with subjects.

2.3.1 Predictive ratings

This method does not require the subjects to be exposed to the actual duration of the vibration. Instead, subjects are exposed for a limited time to different levels of vibration

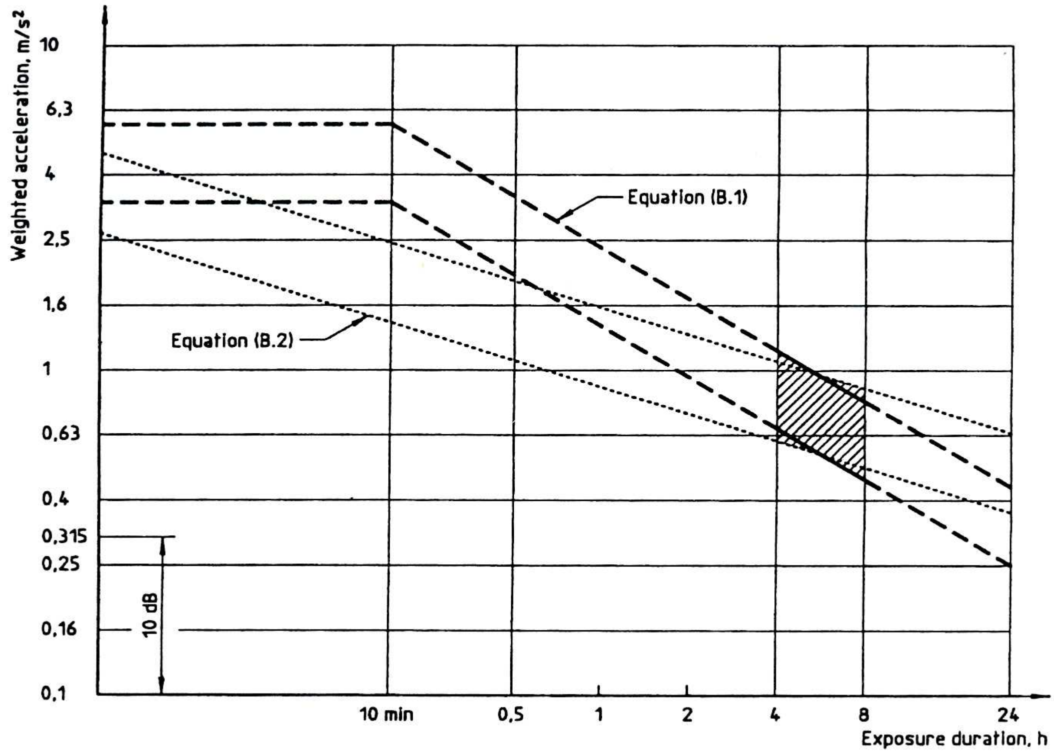


Figure 2.10 Time dependencies proposed in ISO 2631 (1997). Equation (B.1) is based on the conservation of the r.m.s.: $(a)^2 \times t$ = constant. Equation (B.2) is based on the conservation of the r.m.q. or VDV: $(a)^4 \times t$ = constant (taken from the ISO 2631, 1997).

and are asked to predict how long they are able to endure the exposure. Magid *et al*. (1960), Simic (1970), Jones and Saunders (1974), Oborne and Clarke (1974), Jones and Rao (1975), have used this method. However none of these authors have verified the validity of their subjects' judgments. It is probable that the rating of the subjects reflect more the intensity of the stimulus than the tolerance time.

2.3.2 Semantic scale

In this method subjects are provided with a scale containing graded adjectives, for example: 0 - not uncomfortable, 1 - little uncomfortable, 2 – fairly uncomfortable, 3 – uncomfortable, 4 – very uncomfortable, 5 – extremely uncomfortable (semantic scale taken from BS 6841, 1987). Subjects are asked to use the scale to rate their discomfort.

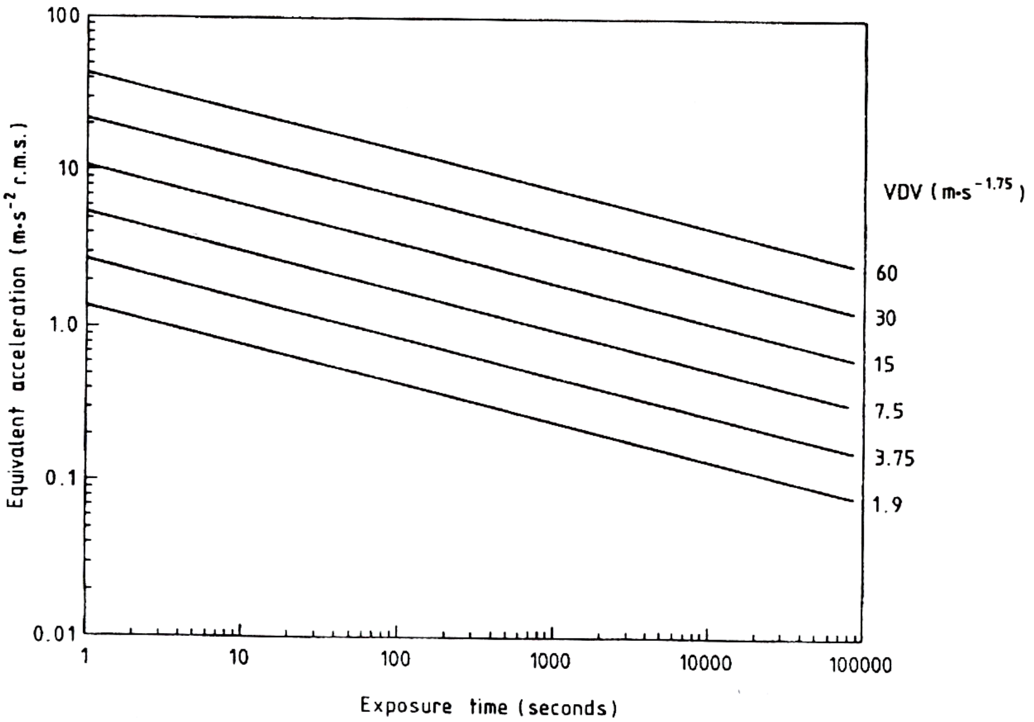


Figure 2.11 Time dependency provided in BS 6841 (1987). It represents the r.m.s. acceleration magnitudes corresponding to vibration dose values from 1.9 $m.s^{-1.75}$ to 60 $m.s^{-1.75}$ for vibration exposure durations from 1 s to 24 h.

Miwa *et al*. (1973) conducted a laboratory experiment, where 10 subjects were exposed to z-axis and *x*-axis whole-body broad-band random vibration for a duration between 2 and 4 hours. Subjects were asked to rate their discomfort every 30 minutes using a 5-level semantic scale. Discomfort increased slightly during the exposure. However it is not possible to conclude that this increase was due to the exposure to vibration as no control condition was included. The discomfort might have increased due to the static posture.

Clarke and Oborne (1975) carried out surveys on trains and on hovercrafts to investigate the reaction of passengers. Each subject rated their discomfort only once during the trip at a freely chosen occasion. No change in discomfort was observed (see Figure 2.2). However as subjects gave only one rating during the trip, this experiment is based on the assumption that the scale used provided the same subjective magnitudes for all subjects. A quantitative interpretation of individual subjective judgments seemed to be mandatory for this experiment but was not conducted. Moreover, the fact that no change in discomfort was observed is not a sufficient basis to conclude that discomfort did not change. The semantic scale method might be too insensitive (Fothergill and Griffin, 1977).

Seidel *et al*. (1980) and Falou *et al*. (2003) conducted experiments where physiological, biomechanical and performance measures have been acquired to investigate the effect of the vibration exposure on the body. The evolution of discomfort was also observed using semantic scales. Subjects were asked to rate their discomfort at regular interval during exposure to vibration. In these two studies a control condition was included. It consisted of asking the subjects to rate their discomfort at regular interval during the duration of the session but with no exposure to vibration. The results showed that discomfort increased with increasing time but the rate of increase was similar with or without exposure to vibration. Therefore the change in discomfort was not due to vibration.

In recent years, muscle activity (EMG) has been measured during exposure to prolonged vibration as well as the evolution of discomfort with time. Sheridan *et al*. (2001) and Michida *et al*. (2001) found that discomfort increased with increasing exposure duration. Their muscle activity results are presented in Section 2.5.1 and in more detail in Chapter 5. However, no control condition was investigated so it is insufficient to conclude that the increase of discomfort observed was due to the exposure to vibration.

2.3.3 Magnitude estimation method

This method consists of presenting to the subjects two stimuli. One stimulus is called the reference and a number is assigned to it. The other stimulus is the test. Subjects have to rate the sensation produced by the test stimulus relative to the sensation produced by the reference stimulus. For example, if the reference is assigned the number 100, and the test stimulus is felt as being twice as uncomfortable as the reference stimulus, subjects are expected to give a rating of 200.

The magnitude estimation method seems to be more sensitive than semantic scaling methods. With semantic scales, the relationship between the semantic labels is not known, whereas it is assumed that a linear and continuous scale results from magnitude estimation.

Clevenson *et al*. (1978) used the magnitude estimation method in a study where 210 subjects participated. The test stimuli consisted of vertical 10-Hz bandwidth random vibration centred at 5 Hz. Each subject was presented the stimulus for one of 9 durations (from 15 s to 60 min) at one of 4 magnitudes. The reference stimulus was a 9-Hz vertical sinusoidal vibration at 0.98 $m.s^{-2}$ r.m.s. for 10 s. For stimuli less than 2 minutes, the reference stimulus was presented before the test stimulus. For stimuli of 2 minutes or longer, the reference was presented after the test. Some of the results are shown in Figure 2.1 and show a decrease in discomfort with an increase in the exposure duration. When using a magnitude estimation test, the reference should provide the same discomfort over the experimental conditions. The discomfort accumulated during the exposure of the test stimulus will almost certainly affect the discomfort produced by the following reference vibration.

Griffin and Whitham (1980) used a slightly different method than the magnitude estimation method (method of constant stimulus). In this method subjects are exposed to a pair of stimuli, one being the reference and the other one the test. But they do not have to give a rating. In this method subjects have three choices. They are required to respond: 1 if ‘motion 1’ is more uncomfortable than ‘motion 2’; 2 if ‘motion 2’ is more uncomfortable than ‘motion 1’; 3 if they want to repeat the pair of motions. This study consisted of different experiments. The first experiment showed (see Figure 2.8) that for 4-Hz, 8-Hz, 16-Hz and 32-Hz sinusoidal vertical vibration, discomfort increased with increasing exposure duration (from 1 to 4 s) but at a slightly different rate for each frequency. The second experiment showed the same effect for an exposure to 8 Hz motions for durations between 1 and 32 s. The effect of the order of the stimuli presentation was also investigated. The rate of increase of discomfort was similar. However the differences observed showed that subjects were more sensitive to the motion presented second. The third experiment investigated the effect of the number of peaks in a vibration on comfort. Each of these motions had the same r.m.s. value but a different number of peaks. It was found that the motion having fewer peaks of higher magnitudes were considered more uncomfortable than motion with more peaks at lower magnitudes. The data points were also fitted with the “r.m.q. equation”: $(a)^4 \times t$ = constant.

2.3.4 Matching method

In the matching method, the subject or the experimenter adjusts the magnitude of a stimulus until the subject considers that it produces a sensation equivalent to a reference stimulus.

Miwa (1968) investigated the effect of the duration of pulse motions on comfort. Subjects were asked to adjust the level of a sinusoid of 3-s duration with pulsed sinusoidal motion of fixed magnitude and duration varying from 0.007 to 6 s. The frequency of the pulse and the matched sinusoidal motion were the same. Frequencies between 2 and 200 Hz were tested. The results showed that discomfort increased with increasing duration until a critical duration. Discomfort did not increase after 2 s of exposure for frequencies between 2 and 60 Hz, or after 0.8 s for frequencies between 60 and 200 Hz. However, as presented previously, other studies do not verify such a critical time limit (Griffin and Whitham, 1980; Kjellberg and Wikström, 1984).

Miwa *et al*. (1973) performed a study where 10 subjects were exposed to 3 hours random vibration. The vibration was stopped every 15 minutes and a sinusoidal vibration at 10 Hz was applied to the subject, of which the magnitude was increased until the subject reached an equivalent sensation. The results showed no changes in the equivalent magnitude of the 10-Hz test vibration. However it cannot be concluded from this result that discomfort did not increase with exposure duration. The subjective discomfort produced by the 10-Hz vibration could have been affected by the preceding motion. Therefore the evolution of the magnitude of the adjusted vibration did not represent the evolution of discomfort.

Griffin and Whitham (1976) conducted an experiment to investigate whether the discomfort time-dependency might depend on the vibration frequency. Subjects were exposed to 4 and 16 Hz vertical vibration. The two frequencies alternated every 10 s. In one session, subjects were asked to adjust the magnitude of 4-Hz vibration to a level producing equivalent discomfort to the 16-Hz vibration. In the other session the order was reversed (i.e., subjects matched the 16-Hz stimulus to the 4-Hz reference). The results showed no change in the setting. They concluded that either there is no time-dependency or that the time-dependency is the same for the two frequencies.

Kjellberg and Wikström (1984) conducted a series of three experiments using the method of matching production. In the first experiment, a vertical 31.5-Hz sinusoidal vibration of 3 s was used as a reference. The test, or matching, vibration was also a 31.5-Hz vibration of

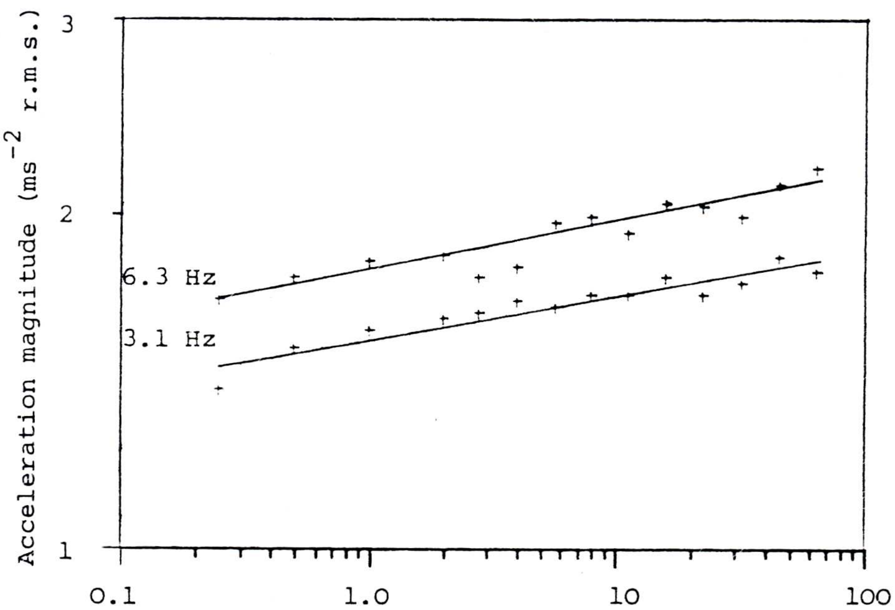


Figure 2.12 The effect of exposure duration (in minutes) on discomfort for 3.1 Hz and 6.3 Hz vibration. Mean sound settings (transformed into vibration magnitudes) as a function of time exposure (taken from Howard, 1986; from a study of Kjellberg and Wikström, 1985).

nine durations, between 0.1 and 4 s. Subjects adjusted the matching motion to the level where it gave rise to the same discomfort level as the reference motion. Subjects participated in two sessions, one with a reference motion of 2.3 $m.s^{-2}$ r.m.s and the other with a reference of 1.1 $m.s^{-2}$ r.m.s. Subjects had as many tries they needed to achieve a match. Results showed that discomfort increased with increasing exposure duration (see Figure 2.9), but no significant difference was observed between the rate of increase in discomfort between the two magnitudes (p>0.05). In the second experiment, a similar method and vibrations were used but the duration increased to 128 s. The matching stimulus had a duration of 3 s and the reference stimuli had duration varying between 1 to 128 s. Similar conclusions were found but a change of growth in the rate of discomfort was observed around 4 s for both 2.3 and 1.1 $m.s^{-2}$ r.m.s. magnitudes. The last experiment employed the same method but instead of using two magnitudes, two frequencies were chosen, 6.3 and 31.3 Hz at magnitudes of respectively 1.1 and 2.3 $m.s^{-2}$ r.m.s. Results also showed that discomfort increased with increasing exposure duration. The time-dependencies observed for the two frequencies presented some differences. For 6.3-Hz vibration, discomfort increased linearly whereas for the 31.5-Hz vibration, after 4 s, discomfort still increased but at a different rate. Therefore after 4 s the linear trend differed significantly between the two frequencies (p<0.01).

Kjellberg and Wikström (1985) employed the method of cross-modality matching to study the development of discomfort during a 1-hour exposure to whole-body vibration. Random vertical vibrations with most energy at either 3.1 or 6.3 Hz were used. The first session consisted of establishing for each subject the link between discomfort produced by a broadband acoustical noise and various vibration levels. Subjects were required to adjust the broadband noise to a level that produced the same discomfort as the vibration. The adjustment was performed at 14 points of time between 0.25 min to 64 min. The results are presented in Figure 2.12. Discomfort increased with increasing exposure duration; however the individual data showed that the trend over time varied widely both within and between subjects. The author suggested that this variability was probably due to the difficulty of the task. If the task was too difficult, subjects might have responded according to what they thought was ‘correct’ rather than what they felt.

2.4 EFFECTS VIBRATION CHARACTERISTICS AND POSTURE ON THE DISCOMFORT TIME-DEPENDENCY

2.4.1 Effects of vibration frequency

Few studies dealing with the effects of vibration frequency on the discomfort time-dependency have been found in the literature. Almost all the studies concerned used vertical vibration at a limited number of frequencies.

Previous cited studies showed a slight or no effect of the vibration frequency on the time-dependency. Griffin and Whitham (1980) used four vertical vibrations at 4, 8, 16 and 32 Hz with durations between 1 cycle and 4 s. Their results indicated that the rate of increase in discomfort with duration was a function of vibration frequency. Kjellberg and Wikström (1984) found that for an exposure of 128 s, the time-dependencies produced by a 6.3 and a 31.5 Hz vertical sinusoidal vibration were significantly different after the 4 seconds of exposure. Griffin and Whitham (1976) investigated the effect of duration on the relative discomfort produced by 4-Hz and 16-Hz sinusoidal vertical whole-body vibration and found that the relationship of the discomfort produced by the two motions was independent of the vibration duration.

2.4.2 Effects of magnitude

Clevenson *et al*. (1978), in their large study presented previously, used random vertical vibrations with a 10-Hz bandwidth centred at 5 Hz at four acceleration levels (0.24, 0.49, 0.73, 0.98 $m.s^{-2}$ r.m.s.) The results showed that the time-dependencies obtained were not dependent on the magnitude of the excitation. However, this study showed that discomfort decreased with increase of the exposure duration.

Kjellberg and Wikström (1984) used vertical 31.5-Hz sinusoidal motions at 1.1 and 2.3 $m.s^{-2}$ r.m.s. and did not find any significant difference in the rate of growth of discomfort between the two time-dependencies ($p>0.05$).

2.4.3 Effects of direction

No specific studies have been performed to investigate the effect of the vibration direction on the time-dependency.

Miwa *et al.* (1973) conducted various experiments investigating the effects of vibration duration on the psychological and physiological responses of the human. Some of these experiments were described in Sections 2.3.2 and 2.3.4. They exposed seated subjects to prolonged (between 2 and 4 hours) low frequency random vibration in the fore-and-aft and vertical directions. They found that the direction of vibration did not affect the discomfort-time dependencies.

2.4.4 Effects of posture

The posture and the body-support offered by a seat probably have critical effects on discomfort and its evolution with exposure duration.

For static postures, muscle activity measured at the backs of the subjects has been reported to decrease when a backrest is inclined backward, or when the lumbar support is increased. Inclination of the seat has only minor effects (Anderson *et al*., 1974). If muscle activity is assumed to be related to discomfort (Hansson *et al*., 1991), the discomfort of seated subject will be reduced by an inclined backrest and a lumbar support.

Studies have shown that posture and body support are critical for the discomfort time-dependency (Michida *et al*., 2001; Sheridan *et al*., 2001). Their results show that the car seat presenting the best ratings of comfort over time allowed body movement and offered sufficient body support. A good car seat design is therefore a clever compromise between support and allowance for movement.

Experiments performed by Hazard (2001) have demonstrated that a "continuously inflating and deflating lumbar support bladder system can reduce low back discomfort, stiffness and fatigue in drivers". This system presented in Figure 2.13 allows both a body support and movement of the low back and can be mounted on any kind of car seat.

All the studies cited in this section did not specified if the discomforts observed due to the posture and body support are due to vibration or due to prolonged static posture.

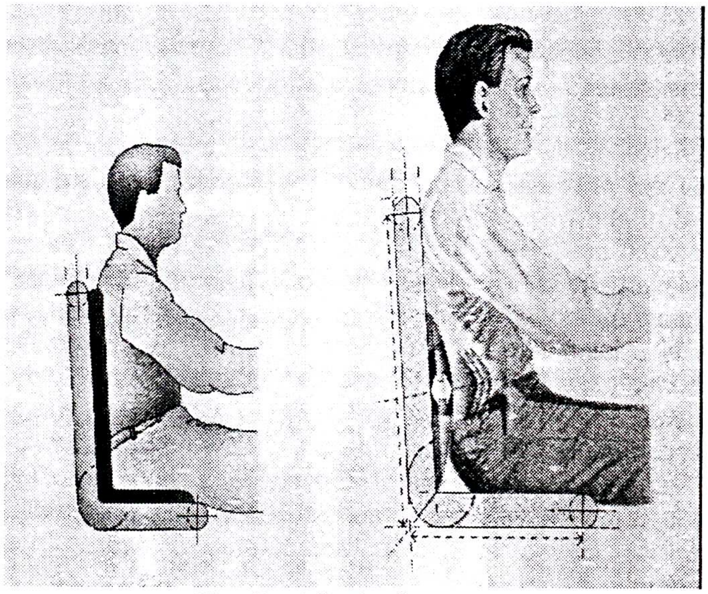
2.5 MEASURES PERFORMED DURING PROLONGED VIBRATION EXPOSURE

2.5.1 Physiological measures

Physiological measures have been undertaken to understand the mechanisms responsible for the observed changes in comfort with time. Studies have been performed to investigate the effects of prolonged exposure to vibration on the body.

Circulatory and respiratory functions such as heart rate, blood pressure, oxygen uptake have been measured (Hornick, 1973). These revealed either an increase in activity at the beginning of exposure followed by a regression towards resting values or a constant level close or slightly above the resting level (Holland, 1966; Miwa *et al*., 1973).

Muscle activity (EMG) is in recent years the most studied physiological effect. Muscle activity is assumed to provide control movements to stabilize the body. Some type of



The BackCycler®

Figure 2.13 Inflating and deflating lumbar support (taken from Hazard, 2001).

muscles activity caused by exposure to vibration might generate stress and therefore discomfort during prolonged exposure. It is not clear whether muscle activity is changed during prolonged exposure but numerous studies (Seidel *et al*., 1980; Hanson *et al*., 1991; Park *et al*., 2001; Michida *et al*., 2001) seem to show an increase of muscle activity and a frequency shift in the EMG of muscles at the neck or the low back. The frequency shift is an observable phenomenon of an increase of muscle 'localized fatigue'. The literature on the effects of vibration on muscle activity is reviewed in more detail in Chapter 5.

2.5.2 Biomechanical measures

It is well known that the body responds differently as a dynamic mechanical system when exposed to vibrations at different frequencies, directions, or magnitudes. For example the whole-body has a resonance in the vertical direction in the range of 4-8 Hz (Griffin, 1990). However few studies have investigated the effects of prolonged vibration on these characteristics.

Seidel *et al*. (1980) studied the point impedance and the transmissibility from a seat to the head for 4-Hz and 8-Hz vertical sinusoidal vibration. Measurements were performed every 20 minutes during a 3-hour exposure. They found a decrease in the transmissibility for 4-Hz and an increase in the transmissibility for 8-Hz vibration with increasing exposure duration. The impedance was not affected by the duration of exposure. The results also indicated that the resonance frequency of the body increased with increasing exposure duration, meaning that the body became stiffer with increasing time.

The seat pressure distribution has also been measured as an indication of the evolution of the posture of subjects during vibration exposure (Michida *et al*., 2001). The results showed that subjects tended to change postures more often as the duration of exposure increased.

2.5.3 Measures of performance

The effects of prolonged exposure to vibration on performance have been studied with different types of task: visual tasks, manual control tasks and cognitive tasks.

Griffin and Lewis (1978), Lewis and Griffin (1978) and McLeod and Griffin (1993) reviewed the research concerning some of these tasks and concluded that there in no evidence of a degradation of performance due to prolonged exposure to vibration.

Seidel *et al*. (1980) conducted an experiment to investigate the effect of prolonged exposure of vibration on vigilance tasks but they did not find any effect.

Falou *et al*. (2003) performed experiments where tracking and reaction time tasks were used but as well, they did not find any effect due to the duration of vibration.

A study from Wilkinson and Gray (1974) even found that vibration increased the performance over time.

Performance is not a measure that can relate to the discomfort caused by the vibration exposure. The subject may maintain the performance level through compensatory measures even if it costs him more to do so.

2.6 LOCATION OF DISCOMFORT DURING PROLONGED EXPOSURE TO VIBRATION

Although much research has been devoted to the determination of the effect of vibration exposure on comfort, little consideration has been given to the source of the discomfort. Even fewer studies have investigated where discomfort is felt after prolonged exposure to vibration. Whole-body vibration can produced different levels of discomfort at different regions in the human body. The effects of frequency, direction, magnitude and duration of the vibration excitation on the body location of discomfort have not been clearly identified. Locating the areas of discomfort may assist the understanding of any interactions between posture and the degree of discomfort and also help in the design of a seat.

Study by Whitham and Griffin (1980) investigated the effects of vibration frequency and direction on the location of discomfort. Subjects were exposed several times to each of six frequencies of vibration (2, 4, 8, 16, 32 and 64 Hz) in the vertical, fore-and-aft and lateral direction. Every stimulus had a magnitude of 1 $m.s^{-2}$ r.m.s. and lasted for 10 seconds. Subjects were seated on a rigid seat without backrest. Subjects were required to mark on a body map, first, where they felt the maximum discomfort. After a second repetition of the motion, subjects were asked to mark any other areas of discomfort. After a further presentation of the stimulus, subjects indicated on a semantic scale their total discomfort. Results in the vertical direction showed maximum sensitivity to vibration acceleration in the range 4 to 16 Hz with discomfort experienced in the upper torso and head. At higher and lower frequencies, discomfort ratings decreased with most discomfort experienced in the lower body, particularly the abdomen and buttocks. Fore-and-aft and lateral excitation produced similar discomfort with areas of most discomfort at the ischial tuberosities. There was a decrease in sensitivity with increasing vibration frequency at constant acceleration. For horizontal vibration, discomfort around the ischial tuberosities could be associated with the sheering motion between the body and the seat.

Maeda *et al.* (2003) conducted a study investigating the relationship between complaints of wheelchair users and the vibration characteristics of the wheelchair. Questionnaires were distributed to 33 wheelchairs. Vibration transmissibility was measured with broadband random vibration in the vertical direction. Results showed that wheelchair users felt the vibration during wheelchair usage at locations on the neck, lower back, and buttocks. They concluded that “the resonance frequency-ranges of the maximum vibration transmissibility of the manual wheelchairs were consistent with the frequency-ranges of the body parts of the causes of the complaints of wheelchair users”. However the resonance frequency of the neck, lower back and buttocks were not measured.

A study by Ravnik (2004) investigated the effects of prolonged car driving on discomfort and the location of discomfort. Subjects were asked at regular intervals, during 3-hours of driving, to indicate where they felt discomfort or pain. Observations were performed according to the CORLETT test (Corlett and Bishop, 1976) on 10 subjects. Results showed that discomfort increased with increasing exposure duration. The locations of discomfort were: 1-neck, 2-lower back, 3-upper back, 4-shoulders, 5-buttocks.

It seems from the few existing studies that areas of discomfort depend greatly on the posture of the subject, the body support available and the vibration characteristics.

2.7 CONCLUSION

Few studies have investigated the effects of prolonged vibration exposure. The reason is most probably the difficulty of observing the evolution of subjective discomfort over time.

No method presented in this section allows the observation and comparison of time-dependencies due to two or more prolonged exposures to vibration.

A majority of the studies reviewed agree that discomfort increased with exposure duration.

Studies investigating the effect of vibration frequency on the evolution of discomfort with exposure duration are rare, and the frequency range that has been studied is limited. The effect of the magnitude of vibration on the evolution of discomfort with exposure duration has been investigated in some studies but the conclusions do not agree. The direction of excitation on the evolution of discomfort with exposure duration has not been studied. Moreover, most studies have been performed with vertical excitation and give little indication of what the effect of duration may be with other directions of excitation. The review of the literature cannot conclude precisely on the possible effects of the vibration characteristics on the discomfort time-dependency.

Muscle activity has been found to increase with increasing exposure duration and seems to be an attractive way to measure the discomfort time-dependency.

The effect of posture and body support has been studied and shows the importance of backrest inclination and lumbar support. However the discomfort observed was not shown to be due to vibration and may have been caused by a prolonged static posture.

This review of the literature indicates that there is a lot unknown about the effects of the duration of vibration on discomfort. The review suggests that the static discomfort should be reduced to observe change with duration of discomfort caused by vibration. It suggests also that a control study where discomfort is assed without exposure to vibration, may dissociate the discomfort due to prolonged exposure to vibration from discomfort caused by prolonged static posture. The objective of this research is to determine the effects of vibration characteristics on the discomfort time-dependency and improve the understandings of the mechanisms of the evolution of discomfort with exposure duration.

The following Chapter 3 presents a new method developed to measure and compare the comfort time-dependencies produced by various stimuli. Chapter 3 uses this new method to investigate the effects of vibration characteristics and body support on the SDTD.

3 SUBJECTIVE STUDY

3.1 INTRODUCTION

The review of the literature presented in Chapter 2 indicated that the effects of the duration of vibration exposure on comfort are not clearly identified. Most studies suggested that discomfort increases with increasing duration of vibration. However, the effects of frequency, magnitude and direction of vibration on the discomfort time-dependency are not known. The literature does not provide clear evidence of the mechanisms of subjective discomfort time-dependencies (SDTD) produced by prolonged exposure to vibration. The International Standard, ISO 2631 (1997), and the British standard BS 6841 (1987) imply that discomfort increases with exposure vibration duration at a rate, which is not affected by the frequency, magnitude or the direction of the vibration. The time-dependencies in standards are provided to account for an increase in discomfort with increasing vibration duration, but they reflect a lack of knowledge of the effects of the vibration characteristics on the SDTD.

The existing methods for measuring discomfort time-dependencies work well for short vibration durations. However they do not seem adapted for prolonged vibration exposures (see Section 2.3 in Chapter 2).

The main objective of this chapter is to investigate the effects of body support, vibration frequency (0.5 Hz, 1 Hz, 4 Hz, 8 Hz and 16 Hz), vibration waveform (sinusoidal, narrowband random and shock stimuli) and vibration direction (lateral, fore-and-aft and vertical) on the discomfort time-dependency.

This chapter proposes a new method elaborated to measure and compare discomfort time-dependencies produced by various stimuli. The subjective discomfort time-dependency was measured at 1 Hz and 4 Hz for sinusoidal and narrowband random vibration in the vertical, lateral and fore-and-aft direction. Narrowband random vibration at 8 Hz and 16 Hz and shocks were also investigated. The effects of body support were studied using a 4-point harness at 1 Hz in the lateral direction. The effects of low frequency vibration were also investigated with a 0.5-Hz stimulus in the fore-and-aft direction. A list of the subjective experiments conducted is presented in Table 1.1. The results of these subjective studies are presented in several ways to assist visualisation of the effects investigated. The results are then discussed and possible mechanisms of the SDTD are developed.

3.2 HYPOTHESES OF THE SUBJECTIVE STUDIES

The review of the literature presented in Chapter 2 suggests that discomfort increases with vibration exposure duration. The lack of studies investigating the effects of frequency, waveform, magnitude and direction of excitation on the subjective discomfort time-dependency (SDTD) could not state clearly how the vibration characteristics may affect the evolution of discomfort with duration.

It was assumed that vibrations producing different body motions could generate different rate of discomfort time dependencies.

From this statement it was hypothesized that:

- Discomfort increases with increasing duration of vibration exposure.
- Discomfort increases at different rates depending on the vibration characteristics (frequency, waveform, direction, magnitude).
- Body support affects the rate of increase in discomfort with exposure duration.
- Discomfort is felt at different locations in the body depending on the vibration characteristics (frequency, waveform, direction). Moreover, the location of discomfort changes during the exposure duration.

Therefore the experiments conducted used various stimuli of various frequencies, waveforms, directions and body supports. The effects of the magnitude of vibration on SDTD were not investigated. It was assumed that the other vibration characteristics (frequency, waveform and direction) were more critical to understanding the mechanisms responsible of the evolution of discomfort with vibration exposure duration.

3.3 OBJECTIVES OF THE SUBJECTIVE STUDIES

The first objective of this chapter is to develop a new method designed to measure and compare discomfort time-dependencies produced by various stimuli.

The second objective is to test the hypothesis that stimuli presenting different vibration characteristics (frequency, waveform and direction) and body support produce different discomfort time-dependencies.

The third main objective of these subjective studies is to gain enough data to be able to develop a model of the mechanisms involved in the production of the SDTD during prolonged exposures to vibration.

Figure 3.1 Subject's environment during a lateral experiment session.

3.4 METHODOLOGY OF THE SUBJECTIVE STUDIES

3.4.1 Introduction

This section mainly described the method designed to evaluate and compare the comfort time-dependencies (Section 3.4.4). It also presents briefly the apparatus and vibration stimuli used (Section 3.4.3 and Section 3.4.5).

The subjective studies are composed of five experiments (magnitude estimation and cross modality, lateral time-dependency, fore-and-aft time-dependency, vertical time-dependency and control). Each experiment was composed of one or more sessions.

For each session, more detailed information on the subjects' environment, subjects' tasks and stimuli are given in Section 3.6. Table 1.1 summarizes all studies, experiments and sessions conducted.

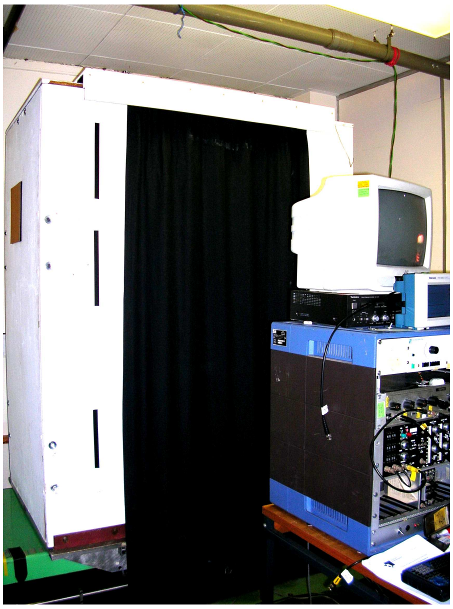


Figure 3.2 White wooden cabin fixed on the horizontal vibrator table.

Figure 3.3 Equipment employed to calibrate the acoustic stimuli used in the static experiment.

3.4.2 Subjects

Male subjects aged between 22 and 28 years participated in the subjective studies. Each session involved 12 subjects. The subjects were selected from the student and staff population of the University of Southampton. The subjects completed a consent form before participating in the experiment. Eight subjects performed all the sessions. The remaining four subjects varied depending on the session. Across all the sessions, a total of 26 subjects participated in the subjective study

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

3.4.3 Apparatus

3.4.3.1 General environment

During the subjective study, subjects sat in a comfortable upright posture, on a conventional car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The footrest was adjusted for each subject to avoid important pressure between the legs and the front of the seat-pan. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt. Table 1.1 summarizes the different environments used. Figure 3.1 shows a subject participating in a subjective experiment with lateral excitation.

For each experiment, the experimenter made sure that no visual or acoustic clues could affect the judgments of the subjects. To control the visual and acoustic environment, in some sessions, subjects were blindfolded and wore headphones producing a 75 dB(A) white noise. Because during 1-Hz and 4-Hz sinusoidal lateral stimuli, after 30 minutes of vibration exposure, some subjects felt sleepy and one subject complained of discomfort due to the headphones, blindfold and headphones were removed and the following sessions used a rigid wooden cabin fitted to the vibrator platform (see Figure 3.2). Subjects sat inside the cabin and did not wear any headphones or blindfold. A camera allowed the experimenter to see the subjects. A fractal image was placed on the cabin wall in front of the subjects (at the height of subject's eyes). For higher frequencies (8-Hz and 16-Hz stimuli), pilot studies showed that the visual field and the vibrator noise could not give clues of the motions. For these frequencies, the cabin was not used and no blindfold or headphones were used. In one condition, subjects wore a 4-point harness to limit their freedom of motion in the lateral direction. For a control study with no motion, subjects sat on the same seat in the same posture in the cabin and were exposed to acoustic stimuli through headphones. The possible effects of the subjects' external environment on the results are discussed in Section 3.8.

Section 3.6 presents a description of all the subjective experiments conducted and indicates for each session the environment used.

3.4.3.2 Motion Generation

Stimuli were created by both *Matlab* (version R6a) and *HVLab* (version 3.81) software. Motion signals were generated and acquired using *HVLab* software (version 3.81). One computer was used to generate the stimuli and another to acquire the motion on the seat. Data were analyzed using *Matlab* software (version R6a). Stimuli were produced by a digital-to-analogue converter and reproduced on a hydraulic vibrator capable of displacements of 1-metre (peak-to-peak). Subjective experiments required two hydraulic vibrators: a 1-m stroke horizontal vibrator and a 1-m stroke vertical vibrator. For both vibrators, cross-axis vibration was less than 5%. Acceleration distortion was greater for the 1-m horizontal vibrator at 0.5 Hz but was less than 8% for all conditions tested. Two accelerometers, Entran EGCS-do-10/V10/LM4, one on the platform and one on the seat bracket, were used to acquire the acceleration. The static experiment required a spectrum analyzer and an acoustic dummy-head in order to calibrate the acoustic stimuli (see Figure 3.3).

3.4.4 Method to measure and compare discomfort time-dependencies

3.4.4.1 Measuring the discomfort time-dependencies

The method developed for the current studies was based on the matching method so as to compare discomfort time-dependencies for different vibration conditions.

In order to observe any change in discomfort over a period *T*, due to a vibration *X*, subjects have to be exposed to the vibration *X* for a duration *T*.

In each session, subjects were exposed to only one stimulus. During the first 10 seconds of the exposure, subjects were asked to focus on the discomfort experienced and use this as a 'reference'. During the rest of the exposure, they were asked to keep their discomfort constant and equal to that during the 'reference'. To be able to perform this task, subjects turned a knob controlling the magnitude of the vibration to which they were exposed.

To help focus the subjects on their task, the magnitude of the stimulus was amplitude modulated. Every 30 seconds, the magnitude increased or decreased by 2 dB (the reference for the calculation of dB was the magnitude of the vibration during the first 10 seconds of exposure). If the magnitude of a vibration is increased, the discomfort felt is expected to increase and so the subject was expected to adjust the knob in order to decrease the magnitude of the vibration.

To cancel the transient effect of the modulation on the subject response, half of the subjects were exposed to a modulation A and the other half to a modulation B, with A and B being 'symmetrical'. This meant that when A produced an increase in magnitude of 2 dB, B produced a decrease in magnitude of the same amount (see Figure 3.4 for an example).

As the subjects had to keep their discomfort constant, a long-term reduction in the vibration amplitude was interpreted as meaning the vibration had increased their discomfort, and vice-versa. Therefore, by measuring the magnitude of the acceleration to which they were exposed during the entire duration of the experiment, the experimenter had access to the changes of acceleration made by the subjects and was able to deduce the subjective discomfort time-dependency.

3.4.4.2 Comparing the subjective discomfort time-dependencies from different stimuli

To allow comparison of the discomfort time-dependencies measured with different vibration stimuli, each session started with a stimulus that produced the same discomfort. A magnitude estimation test was used for this purpose. Prior to each subjective experiment in which SDTD was assessed, subjects participated in a magnitude estimation test to determine their scale of subjective magnitudes for the stimulus, so that it could be presented at the same equivalent discomfort during the first 10 seconds of exposure. Figure 3.5 shows an example of how the experimental data were used to calculate the magnitudes of vibration giving equivalent discomfort. The data are taken from a pilot study with one subject. In this example the reference stimulus is a 4-Hz sinusoidal vibration at 0.25 $m.s^{-2}$ r.m.s. The subject was asked to associate the value 100 to the judgment of the reference stimulus. Sinusoidal test stimuli at 1 Hz and 4 Hz with magnitudes varying between 0.10 $m.s^{-2}$ r.m.s. and 1.00 $m.s^{-2}$ r.m.s. are employed. The measured data are plotted on the graph, Figure 3.5, with the acceleration magnitude on the abscissa and the subjective magnitude on the ordinate. The data are curve-fitted using Stevens' power law: $\Psi = k.\varphi^{n}$, where Ψ is the psychophysical magnitude (subjective judgment) of the stimulus and φ is its physical magnitude (acceleration). In this example the goal of the magnitude estimation test is to find the magnitude of a 1-Hz sinusoid that produces, during the first 10 seconds of exposure, a discomfort equivalent to that produced by a 10-second 4-Hz sinusoid at 0.5 $m.s^{-2}$ r.m.s. Both equations presented in Figure 3.5 are used to calculate the equivalent magnitude of the 1-Hz sinusoid. The subjective judgment, Ψ for a 4-Hz sinusoid at 0.5 $m.s^{-2}$ r.m.s., is obtained using the equation: $\psi = 723.85 \cdot 0.5^{1.473}$ = 260.8 (obtained from the 4-Hz experimental data, curve-fitted with the Stevens' power law). The equivalent magnitude of the 1-Hz sinusoid is obtained using the equation: $260.8 = 496.66 \cdot \varphi^{0.64}$ (obtained from the 1-Hz experimental data, curve-fitted with the Stevens' power law), which gives φ = 0.36 $m.s^{-2}$ r.m.s. Therefore, if the subjective discomfort time-dependency of a 4-Hz sinusoid stimulus, starting at 0.5 $m.s^{-2}$ r.m.s., is to be compared with the subjective discomfort time-dependency of a 1-Hz sinusoid, the 1-Hz vibration should start with a magnitude of 0.36 $m.s^{-2}$ r.m.s.

The reference stimulus used in the magnitude estimations tests is not always the reference stimulus of the whole subjective studies (which was defined as a lateral 10 seconds 4-Hz sinusoid at 0.5 $m.s^{-2}$ r.m.s.). In this example the reference stimulus used for the magnitude estimation test was a 10 seconds 4-Hz sinusoid at 0.25 $m.s^{-2}$ r.m.s., whereas the reference stimulus of these subjective studies is a 10 seconds 4-Hz sinusoid at 0.5 $m.s^{-2}$ r.m.s. The main reason of using a different magnitude is to optimize the spread of the subjective judgments above and below the judgment of the reference stimulus, which is usually 100. By optimizing the spread of the judgment values around 100, the task of the subject will be facilitated and the accuracy of the curve-fitting will be improved In this example it can be expected (from comfort contour curves presented in standards such as ISO 2631, 1997; see Section 3.7.1) that the magnitude of a 10 seconds 1-Hz sinusoidal stimulus required to produced an equivalent discomfort of a 10 seconds 4-

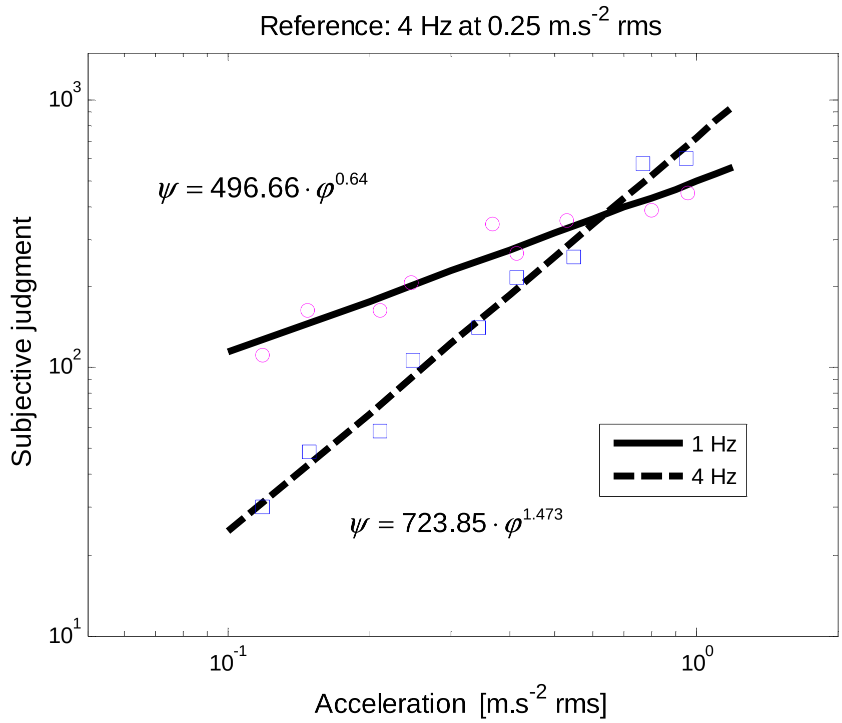


Figure 3.5 Example of data obtained with the magnitude estimation test.

Hz sinusoid at 0.5 m.s^{-2} r.m.s. is lower than 0.5 m.s^{-2} r.m.s.. Therefore to reduce unnecessary vibration exposure of the subjects and to optimize the spread of their subjective judgments, it is better to use, for the magnitude estimation test, a reference stimulus with a magnitude less than 0.5 m.s^{-2} r.m.s..

3.4.4.3 Location of discomfort during prolonged vibration exposure

Different stimuli are expected to produce discomfort at different locations in the body. Moreover, the location of discomfort may change during the exposure duration. Semantic scales were used to determine where in the body discomfort was felt during prolonged exposure to vibration and how this discomfort evolved during the vibration duration. Subjects were, first, asked to identify, every 5 or 10 minutes, the location where most discomfort was experienced in the body, and rate this discomfort with a semantic scale between 0 and 5 (0 - not uncomfortable, 1 - little uncomfortable, 2 - fairly uncomfortable, 3 - uncomfortable, 4 - very uncomfortable, 5 - extremely uncomfortable, from British standard 6841, 1987). Then they were asked to give any other locations of discomfort and their corresponding ratings. Subjects could use any word to describe their location of discomfort. Analysis used all words mentioned and when appropriate regrouped words designing a similar location.

3.4.5 Vibration stimuli

It was assumed that vibrations producing different body responses could generate different discomfort time-dependencies.

The apparent mass and seat-to-head transmissibility have shown different responses of the body at 1 Hz and 4 Hz (resonance in seat-to-head transmissibility at 1 Hz in the fore-and-aft direction, resonance of the seated body at 4 Hz in the vertical direction, Griffin, 1990). The direction of excitation also affects the seat-to-head transmissibility (Paddan and Griffin, 1996). Therefore 1-Hz and 4-Hz stimuli lasting 1 hour were used in lateral, fore-and-aft, and vertical directions. To investigate the effects of low frequencies on the comfort time-dependency, a 0.5-Hz sinusoidal stimulus was used in the fore-and-aft direction during 15 minutes.

Higher frequencies and narrowband random motions, and also shocks were investigated because they are commonly encountered in transport. Therefore one-third octave narrowband random vibration centred at 8 Hz and 16 Hz were used during 30 minutes to investigate further the effects of frequency on the subjective discomfort time-dependencies (SDTD). Shock stimuli lasting 1 hour were also investigated. The shock waveform was build with 1.5 cycle of a magnitude modulated 1-Hz sinusoid (see Figure 3.6), with one shock every 10 seconds. To investigate the effects of the waveform of the excitation on the SDTD, 1-Hz and 4-Hz narrowband random vibration were also used in the three directions.

The reference stimulus was a 4-Hz fore-and-aft sinusoid at 0.5 m.s-2 r.m.s. This magnitude was chosen because it is common to various types of vehicles (Griffin, 1990).

Because a harness restricts the body motion and therefore could affect the body response to an excitation, a 4-point harness was used during exposure to a 1-Hz lateral sinusoid during 15 minutes.

More details on each session conducted are given in Section 3.6.6, and summarized in Table 1.1.

3.5 DATA ANALYSIS METHOD

3.5.1 Subjective discomfort time-dependencies

The acceleration time history was acquired to a computer during the entire duration of each subject's exposure. From the time data, the r.m.s acceleration was calculated with an integration time of 5 seconds. Data were plotted using only the last two r.m.s. values over a 30-second interval. As the excitation magnitude was modulated every 30 seconds, at the beginning of the interval subjects would turn the knob to adjust the acceleration to a level of discomfort that represents what they experienced during the first 10 seconds of the session. The last 10 seconds of the 30-second period were assumed to show the result of their judgment and be representative of their equivalent discomfort. For 1-Hz and 4-Hz vertical narrowband random stimuli, the variability in the magnitude was such that the integration time had to be increased to 30 seconds.

The magnitude estimation tests for each subject and for each stimulus provided an acceleration magnitude that produced the same level of discomfort during the first 10 seconds of exposure. Each subject was therefore presented with a slightly different magnitude of vibration. In order to compare the discomfort time-dependency between subjects and between stimuli, the calculated r.m.s. values were normalised. The vibration magnitudes were divided by the first r.m.s acceleration data point so that all the discomfort

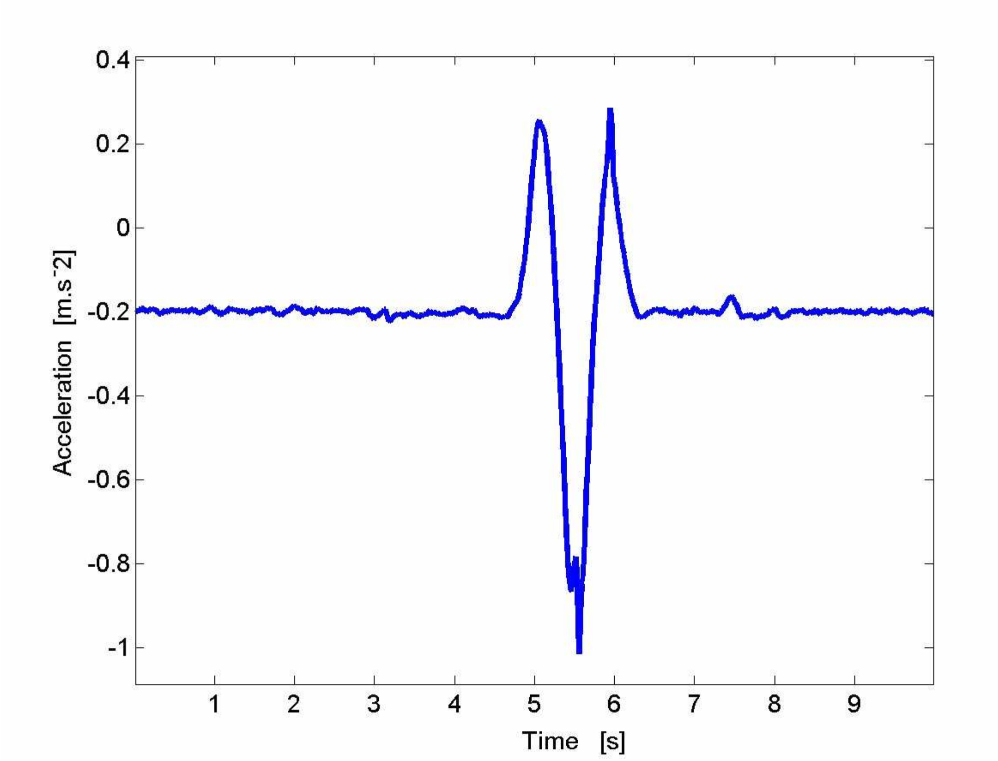


Figure 3.6 Waveform of the shock stimulus measured on the vibrator platform.

time-dependency curves started at 1.0. The curves presented in Section 3.7 represent the median normalised r.m.s acceleration data obtained from the 12 subjects.

3.5.2 Location of discomfort

Every 5 or 10 minutes (depending on whether the total duration of the experiment was 30 minutes or 60 minutes), subjects reported the locations where discomfort was experienced and their corresponding ratings. For each location mentioned, discomfort ratings were averaged and the median values were calculated over the 12 subjects.

3.6 EXPERIMENTS CONDUCTED IN THE SUBJECTIVE STUDY

3.6.1 Introduction

The subjective studies conducted consist in a total of 27 sessions grouped in different experiments (see Table 1.1). The experiments conducted are described in the following sections. They are not presented in the chronological order in which they were conducted.

3.6.2 Magnitude estimation and cross modality experiments

3.6.2.1 Overview

As described in Section 3.5.3, to compare the discomfort time-dependencies produced by different stimuli, each stimulus should generate, during the first 10 seconds of exposure, a similar level of discomfort. The level of discomfort chosen to be the reference for all stimuli was the subjective discomfort produced during exposure to a 10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.. Equivalent discomfort magnitudes were obtained for the following investigated stimuli:

- 10-second, 1-Hz sinusoid in the lateral direction,
- 10-second, one-third octave band random vibration centered at 1 Hz in the lateral direction,
- 10-second, one-third octave band random vibration centered at 4 Hz in the lateral direction,
- 10-second, 1-Hz shocks stimulus in the lateral direction,
- 10-second, 4-Hz sinusoid in the fore-and-aft direction,
- 10-second, 1-Hz sinusoid in the fore-and-aft direction,
- 10-second, one-third octave band random vibration centered at 1 Hz in the fore-and-aft direction,

- 10-second, one-third octave band random vibration centered at 4 Hz in the fore-and-aft direction,
- 10-second, 1-Hz sinusoid in the fore-and-aft direction,
- 10-second, 4-Hz sinusoid in the vertical direction,
- 10-second, 1-Hz sinusoid in the vertical direction,
- 10-second, one-third octave band random vibration centered at 1 Hz in the vertical direction,
- 10 second, one-third octave band random vibration centered at 4 Hz in the vertical direction.
- 10-second, 1-Hz sinusoid in the vertical direction,

The equivalent discomfort magnitudes of the stimuli were calculated using the magnitude estimation method (described in Section 3.5.3.2). This method requires the subjects to judge the discomfort produced by a test stimulus relatively to a reference stimulus. The reference stimulus being in the lateral direction (4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.), and the vibrator platform used being uni-directional, it was not possible to compare directly the lateral reference with vertical or fore-and-aft test stimuli. Therefore the equivalent magnitudes of the test stimuli in the vertical and fore-and-aft directions were assessed by using an acoustic stimulus. All equivalent magnitudes were obtained in three sessions, all using magnitude estimation and cross modality tests. These sessions are described in the following sections.

3.6.2.2 Session 1: Lateral direction session (Magnitude estimation and cross modality tests).

Subject environment:

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt. Subjects were blindfolded and wore headphones producing a 75 dB(A) white noise.

Magnitude estimation tests:

The magnitudes required for the lateral stimuli to produce a discomfort equivalent to a 10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s. were calculated using the classical magnitude estimation method described in Section 3.5.3.2. Results are presented in Section 3.7.1.

Cross modality tests:

To determine the equivalent comfort magnitudes of stimuli in the fore-and-aft and vertical directions, magnitude estimation tests were performed between the vibration reference and acoustic test stimuli.

The acoustic test stimuli were 10-second duration, 1000-Hz sinusoids between 45 and 85 dB(A). The acoustic stimuli were generated by *HVLab* (version 3.81) software and calibrated using a spectrum analyser and an acoustic dummy-head equipped.

Using the magnitude estimation method, the magnitude of the acoustic stimulus that produced a similar level of discomfort to the lateral vibration reference (a 10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.) was calculated for each subject.

3.6.2.3 Session 2: Fore-and-aft direction session (Cross modality and magnitude estimation tests).

Subject environment:

In the following sessions, the subject environment was modified. A rigid wooden cabin was mounted on the vibrator platform and the blindfold was not used. Subjects wore headphones (the possible effects of the different environments used on the subjective results are discussed in Section 3.8.1). The posture of the subjects remained the same. Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform.

Cross modality tests:

Each subject started the session with a magnitude estimation test between the equivalent acoustic stimulus (calculated during the previous cross modality test, see previous section) used as reference and 10-second, 4-Hz fore-and-aft sinusoids between 0.1 and 1.0 $m.s^{-2}$ r.m.s. This test allows the calculation of the magnitude of the 10-second, 4-Hz fore-and-aft sinusoid required to produce a discomfort level equivalent to the reference (10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.).

Magnitude estimation tests:

Magnitude estimation tests were then conducted using a 10-second 4-Hz fore-and-aft sinusoid at 0.25 $m.s^{-2}$ r.m.s. as reference and 1-Hz and 4-Hz fore-and-aft stimuli (as described in Section 3.6.2.1) as test stimuli.

Then using the Stevens' power law (shown in Section 3.4.4.2), the equivalent discomfort magnitudes of all fore-and-aft stimuli can be calculated with the magnitude of the 10-

second, 4-Hz fore-and-aft sinusoid determined by cross modality test. The magnitudes of the fore-and-aft stimuli required to produce an equivalent discomfort as the one generated by the reference stimulus (10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.) were determined for each subject.

3.6.2.4 Vertical direction session: cross modality and magnitude estimation tests

The procedure conducted for the fore-and-aft stimuli presented in the previous section was also applied for the vertical stimuli.

Subject environment:

The rigid wooden cabin used in the fore-and-aft direction was mounted on the vertical vibrator platform. Subjects did not wear blindfold but wore headphones. Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on the vibrator platform.

Cross modality tests:

Each subject started the session with a magnitude estimation test between the equivalent acoustic stimulus (calculated during the cross modality test conducted in the lateral direction, see Section 3.6.2.2) used as reference and 10-second, 4-Hz vertical sinusoids between 0.1 and 1.0 $m.s^{-2}$ r.m.s. used as test stimuli. This test allows the calculation of the magnitude of the 10-second, 4-Hz vertical sinusoid required to produce a discomfort level equivalent to the reference stimulus (a 10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s.).

Magnitude estimation tests:

Magnitude estimation tests were then conducted using a 10-second, 4-Hz vertical sinusoid at 0.25 $m.s^{-2}$ r.m.s. as reference and 1-Hz and 4-Hz fore-and-aft stimuli (as described in Section 3.6.2.1) as test stimuli.

Then using the Stevens' power law (shown in Section 3.4.3.2), the equivalent discomfort magnitudes of all vertical stimuli could be calculated with the magnitude of the 10-second, 4-Hz vertical sinusoid determined by cross modality test.

Therefore all the magnitudes of all lateral, fore-and-aft and vertical stimuli required to produce an equivalent discomfort as the one generated by the 10-second, 4-Hz lateral sinusoid at 0.5 $m.s^{-2}$ r.m.s. were known for each subject.

3.6.3 Subjective discomfort time-dependency experiments with lateral oscillation

3.6.3.1 Sessions 1 to 5: effects of low frequencies (1 Hz and 4 Hz) and waveform (sinusoids, narrowband random and shock motions) on the SDTD

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

Subjects were blindfolded and wore headphones producing a 75 dB(A) white noise.

Session 1: Subjective discomfort time-dependency produced by 4-Hz lateral sinusoids during 60 minutes of exposure

Each subject was exposed during one hour to a 4-Hz lateral sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

During the first 10 seconds of exposure the magnitude of the 4-Hz lateral sinusoid was 0.5 $m.s^{-2}$ r.m.s. for all 12 subjects.

Session 2: Subjective discomfort time-dependency produced by 1-Hz lateral sinusoids during 60 minutes of exposure

Each subject was exposed during one hour to a 1-Hz lateral sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25^{th} and 75^{th} percentiles of the magnitude of the 10-second 1-Hz lateral sinusoid were, respectively, 0.25 and 0.34 $m.s^{-2}$ r.m.s. with a median value of 0.30 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 3: Subjective discomfort time-dependency produced by lateral one-third octave narrowband vibration centered at 4 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a lateral one-third octave narrowband vibration centered at 4 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentiles of the magnitude of the 10-second one-third octave narrowband vibration centered at 4 Hz were, respectively, 0.36 and 0.51 $m.s^{-2}$ r.m.s. with a median value of 0.45 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 4: Subjective discomfort time-dependency produced by lateral one-third octave narrowband vibration centered at 1 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a lateral one-third octave narrowband vibration centered at 1 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentile of the magnitude of the 10-second one-third octave narrowband vibration centered at 1 Hz were, respectively, 0.22 and 0.30 $m.s^{-2}$ r.m.s. with a median value of 0.27 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 5: Subjective discomfort time-dependency produced by a lateral shock motion during 60 minutes of exposure

Each subject was exposed during one hour to a lateral shock stimulus (one shock every 10 seconds). During the first shock, subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentile of the magnitude of the 10-second lateral shock motion were, respectively, 0.19 and 0.26 $m.s^{-2}$ r.m.s. with a median value of 0.23 $m.s^{-2}$ r.m.s.

3.6.3.2 Session 6 and 7: Subjective discomfort time-dependency produced by high frequencies (8-Hz and 16-Hz) of lateral vibration during 30 minutes of exposure

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

For these conditions, the headphones and blindfold were not used. At these frequencies (8 Hz and 16 Hz) the subjects could not perceive any visual clue of the motions. Similarly the experimenter made sure that no acoustic clue could be perceived.

Session 6: Subjective discomfort time-dependency produced by a lateral one-third octave narrowband vibration centered at 8 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a lateral one-third octave narrowband vibration centered at 8 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was 0.81 $m.s^{-2}$ r.m.s. for all subjects. Magnitude estimation tests were not performed for stimuli at 8-Hz and 16-Hz. The equivalent comfort magnitudes were determined according to the frequency weighting curves and weighting factors presented in International Standard ISO 2631 (1997). The transmissibility of the seat-pan and backrest was also considered in the calculation. The details of the calculation are presented in Section 3.7.1.

Session 7: Subjective discomfort time-dependency produced by a lateral one-third octave narrow-band vibration centered at 16 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a lateral one-third octave narrow-band vibration centered at 16 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of was 1.31 $m.s^{-2}$ r.m.s. for all subjects. The details of the calculation are presented in the Section 3.7.1.

3.6.3.3 Session 8: Subjective discomfort time-dependency with subjects wearing a 4-point harness and exposed to 1-Hz lateral sinusoidal vibration during 30 minutes

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform.

Subjects wore a 4-point harness to restrain the motions of their bodies.

Subjects were blindfolded and wore headphones producing a 75 dB(A) white noise.

Each subject was exposed during 30 minutes to a 1-Hz lateral sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used for the first 10 seconds of the 1-Hz lateral sinusoid was 0.30 $m.s^{-2}$ r.m.s. (as for the session 2).

3.6.4 Subjective *discomfort time-dependency* experiments with fore-aft oscillation

3.6.4.1 Session 1 to 5: Effects of low frequencies (1-Hz and 4-Hz) and waveform (sinusoids, narrowband random and shock motions) on the SDTD

Subject environment

A rigid wooden cabin was fitted to the vibrator platform (see Figure 3.2). Subjects sat inside the cabin and did not wear any headphones or blindfold. Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

Session 1: Subjective discomfort time-dependency produced by a 4-Hz fore-and-aft sinusoid during 60 minutes of exposure

Each subject was exposed during one hour to a 4-Hz fore-and-aft sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used for all subjects, during the first 10 seconds of exposure was 0.23 $m.s^{-2}$ r.m.s. This magnitude is the median of the equivalent discomfort magnitudes determined by the magnitude estimation method (the 25th and 75th percentile of the equivalent comfort magnitude were, respectively, 0.18 and 0.26 $m.s^{-2}$ r.m.s.).

Session 2: Subjective discomfort time-dependency produced by a 1-Hz fore-and-aft sinusoid during 60 minutes of exposure

Each subject was exposed during one hour to a 1-Hz fore-and-aft sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentile of the equivalent discomfort magnitude were, respectively, 0.20 and 0.31 $m.s^{-2}$ r.m.s., with a median value of 0.26 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 3: Subjective discomfort time-dependency produced by fore-and-aft one-third octave narrowband vibration centered at 4 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a fore-and-aft one-third octave narrow-band vibration centered at 4 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentiles of the equivalent discomfort magnitude were, respectively, 0.17 and 0.31 $m.s^{-2}$ r.m.s., with a median value of 0.21 $m.s^{-2}$ r.m.s. (see Section 4.7.1).

Session 4: Subjective discomfort time-dependency produced by fore-and-aft one-third octave narrow-band vibration centered at 1 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a fore-and-aft one-third octave narrow-band vibration centered at 1 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subjects. Within the 12 subjects, the 25th and 75th percentiles of the equivalent discomfort magnitude were, respectively, 0.21 and 0.29 $m.s^{-2}$ r.m.s., with a median value of 0.25 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 5: Subjective discomfort time-dependency produced by a fore-and-aft shock motion during 60 minutes of exposure

Each subject was exposed during one hour to a fore-and-aft shock stimulus (one shock every 10 seconds). During the first shock subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subjects. Within the 12 subjects, the 25^{th} and 75^{th} percentiles of the equivalent discomfort magnitude were, respectively, 0.19 and 0.28 $m.s^{-2}$ r.m.s., with a median value of 0.24 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

3.6.4.2 Session 6 and 7: Subjective discomfort time-dependency produced by high frequencies (8-Hz and 16-Hz) of fore-and-aft vibration during 30 minutes of exposure

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

For these conditions, the headphones and blindfold were not used.

Session 6: Subjective discomfort time-dependency produced by a fore-and-aft one-third octave narrow-band vibration centered at 8 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a fore-and-aft one-third octave narrowband vibration centered at 8 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was 0.61 $m.s^{-2}$ r.m.s. for all 12 subjects. The details of the calculation are presented in the Section 3.7.1.

Session 7: Subjective discomfort time-dependency produced by a fore-and-aft one-third octave narrow-band vibration centered at 16 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a fore-and-aft one-third octave narrow-band vibration centered at 16 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was 1.10 $m.s^{-2}$ r.m.s. for all 12 subjects. The details of the calculation are presented in the Section 3.7.1.

3.6.4.3 Session 8: Subjective discomfort time-dependency produced by a 0.5-Hz fore-and-aft sinusoids during 30 minutes of exposure

Subject environment

The cabin was not used in this session.

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform.

Subjects were blindfolded and wore headphones producing a 75 dB(A) white noise.

Each subject was exposed during 30 minutes to a 0.5-Hz fore-and-aft sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used for the first 10 seconds of the 0.5-Hz fore-and-aft sinusoid was 0.28 $m.s^{-2}$ r.m.s. for all 12 subjects. Magnitude estimation tests were not performed for the 0.5-Hz stimulus. The equivalent discomfort magnitude was determined according to the frequency weighting curves and weighting factors presented in International Standard ISO 2631 (1997). The transmissibility of the seat-pan and backrest was also considered in the calculation. The details of the calculation are presented in Section 3.7.1.

3.6.5 Subjective discomfort time-dependency experiments with vertical oscillation

3.6.5.1 Sessions 1 to 5: Effects of low frequencies (1 Hz and 4 Hz) and waveform (sinusoids, narrowband random and shock motions) on the SDTD

Subject environment

A rigid wooden cabin was fitted to the vibrator platform (see Figure 3.2). Headphones and blindfold were not used.

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

Session 1: Subjective discomfort time-dependency produced by a 4-Hz vertical sinusoid during 60 minutes of exposure

Each subject was exposed during one hour to a 4-Hz vertical sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used for all subjects, during the first 10 seconds of exposure was 0.22 $m.s^{-2}$ r.m.s. This magnitude is the median of the equivalent discomfort magnitudes determined by the magnitude estimation method (the 25^{th} and 75^{th} percentiles of the equivalent discomfort magnitude were, respectively, 0.18 and 0.26 $m.s^{-2}$ r.m.s.).

Session 2: Subjective discomfort time-dependency produced by a 1-Hz vertical sinusoid during 60 minutes of exposure

Each subject was exposed during one hour to a 1-Hz vertical sinusoid. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25^{th} and 75^{th} percentiles of the equivalent discomfort magnitude were, respectively, 0.37 and 0.49 $m.s^{-2}$ r.m.s., with a median value of 0.44 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 3: Subjective discomfort time-dependency produced by a vertical one-third octave narrowband vibration centered at 4 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a vertical one-third octave narrowband vibration centered at 4 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25^{th} and 75^{th} percentiles of the equivalent discomfort magnitude were, respectively, 0.15 and 0.24 $m.s^{-2}$ r.m.s., with a median value of 0.18 $m.s^{-2}$ r.m.s. (see Section 3.7.1).

Session 4: Subjective discomfort time-dependency produced by a vertical one-third octave narrow-band vibration centered at 1 Hz during 60 minutes of exposure

Each subject was exposed during one hour to a vertical one-third octave narrow-band vibration centered at 1 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentiles of the equivalent discomfort magnitude were, respectively, 0.35 and 0.52 m.s^{-2} r.m.s., with a median value of 0.46 m.s^{-2} r.m.s. (see Section 3.7.1).

Session 5: Subjective discomfort time-dependency produced by a vertical shock motion during 60 minutes of exposure

Each subject was exposed during one hour to a vertical shock stimulus (one shock every 10 second). During the first shock subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds of exposure was the equivalent discomfort magnitude determined by the magnitude estimation method for each subject. Within the 12 subjects, the 25th and 75th percentiles of the equivalent discomfort magnitude were, respectively, 0.29 and 0.41 m.s^{-2} r.m.s., with a median value of 0.34 m.s^{-2} r.m.s.

3.6.5.2 Session 6 and 7: Subjective discomfort time-dependency produced by high frequencies (8-Hz and 16-Hz) of vertical vibration during 30 minutes of exposure

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the vibrator platform, with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform. For safety, subjects wore a loose lap belt.

For these conditions, the headphones and blindfold were not used.

Session 6: Subjective discomfort time-dependency produced by a vertical one-third octave narrowband vibration centered at 8 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a vertical one-third octave narrowband vibration centered at 8 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

Table 3.1 Median of the equivalent discomfort magnitude obtained with magnitude estimation and cross modality tests

	Lateral		Fore-and-aft		Vertical	
	4-Hz	1-Hz	4-Hz	1-Hz	4-Hz	1-Hz
Median r.m.s. acceleration of sinusoidal stimuli obtained by magnitude estimation test [$m.s^{-2}$ r.m.s.]	0.5 (ref)	0.30	0.23	0.26	0.22	0.44
Median r.m.s. acceleration of narrowband random stimuli obtained by magnitude estimation test [$m.s^{-2}$ r.m.s.]	0.45	0.27	0.21	0.25	0.20	0.42
Median r.m.s. acceleration of shock stimuli obtained by magnitude estimation test [$m.s^{-2}$ r.m.s.]		0.25		0.24		0.34

The magnitude used during the first 10 seconds was 0.33 $m.s^{-2}$ r.m.s. for all 12 subjects. The details of the calculation are presented in Section 3.7.1.

Session 7: Subjective discomfort time-dependency produced by a vertical one-third octave narrow-band vibration centered at 16 Hz during 30 minutes of exposure

Each subject was exposed during 30 minutes to a vertical one-third octave narrow-band vibration centered at 16 Hz. During the first 10 seconds of exposure subjects had to focus on the discomfort experienced and keep this level of discomfort constant during the remaining session by adjusting the magnitude of the motion with a knob.

The magnitude used during the first 10 seconds was 0.45 $m.s^{-2}$ r.m.s. for all 12 subjects. The details of the calculation are presented in Section 3.7.1.

3.6.6 Control study with no oscillation

It was desired that in the dynamic studies only the vibration would cause discomfort. However, during prolonged sitting the posture might also contribute to discomfort. A control study was therefore performed to investigate the variation in static discomfort over time.

Subject environment

Subjects sat in a comfortable upright posture, on a car seat, rigidly fixed on the floor, with their feet supported on an adjustable footrest. The headrest was removed from the seat. Subjects were wearing headphones and a blindfold.

Session 1: Static study

The procedure used during the control study was similar to the method designed for the dynamic studies. Subjects sat for one hour on a fixed car seat. Instead being exposed to vibration they were exposed to an amplitude modulated white noise through headphones. They were asked to control the sound pressure level of the white noise by turning a knob so as to maintain the loudness constant over the total duration of the experiment. Subjects were also asked to give ratings of discomfort and indicate the location of discomfort, at the beginning of the session and every 10 minutes (as in the dynamic studies).

The location and rating of static discomfort was compared between the static and the dynamic studies to anticipate the part that static discomfort played in the dynamic discomfort studies.

3.7 RESULTS

3.7.1 Magnitude estimation and cross modality

3.7.1.1 Subject judgments of magnitude estimation in cross modality tests

For 1-Hz and 4-Hz stimuli, magnitude estimation and cross modality tests have been used to determine the magnitudes of all stimuli required to produce a discomfort equivalent to a 10-second 4-Hz lateral sinusoid at 0.5 m.s^{-2} r.m.s.

Table 3.1 presents the median values of the equivalent discomfort magnitudes. The equivalent discomfort magnitudes vary between directions and frequencies of excitation but not as much between the sinusoids, narrowband random, and shock stimuli.

3.7.1.2 Comfort contours as predicted by ISO 2631 (1997)

This section presents the calculation of the magnitudes of the sinusoid investigated in the subjective study to produce a similar level of discomfort of a 10-second 4-Hz lateral sinusoid at 0.5 m.s^{-2} r.m.s.

It was assumed that two vibrations of the same duration produce an equivalent level of discomfort if their weighted r.m.s. accelerations are equal. The weighted r.m.s. is expressed according to the following equation:

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

where,

$a_W(t)$ is the weighted acceleration express in meters per second squared (for translational vibrations)

T is the duration of the measurement, in second.

For a seated body in contact with the backrest, the vibration enters the body at three locations: feet, seat surface and backrest. The total weighted r.m.s. acceleration of the seated body is calculated from the weighted r.m.s. acceleration measured at the feet, seat surface and backrest by the following equation:

$$a_{WT} = \left[a_{Wfeet}^2 + a_{Wseat-surface}^2 + a_{Wbackrest}^2\right]^{\frac{1}{2}}$$

where,

a_{WT} is the total weighted r.m.s. acceleration of the seated body

a_{Wfeet} is the weighted r.m.s. acceleration at the feet

$a_{Wseat\text{-}surface}$ is the weighted r.m.s. acceleration at the seat-surface

$a_{Wbackrest}$ is the weighted r.m.s. acceleration at the backrest

The weighted accelerations are calculated using the weighting factors given in ISO 2631 (1997). The standard indicates which frequency weighting curves to use depending on the direction of the vibration, the location of the measure (feet, seat-surface and backrest), the posture of the body (seated, standing or recumbent) and whether evaluating vibration with respect to health, comfort, perception or motion sickness. Table 3.2 indicates, depending on the frequency, direction and localization, what frequency weighting factors to consider for evaluating comfort. The standard also gives multiplying factors that depend on the localization of the input vibration and the direction. Table 3.3 presents these multiplying factors. The weighted r.m.s. acceleration can be assimilated (for tonal sinusoidal vibrations) to the r.m.s. acceleration multiplied by the frequency weighting factors multiplied by the direction multiplying factors.

Table 3.2 Frequency weighting factors from ISO 2631 (1997)

	Lateral	Fore-and-aft	Vertical
	feet	feet	feet
	Wk	Wk	Wk
0.5 Hz	0.418	0.418	0.418
1.0 Hz	0.462	0.462	0.462
4.0 Hz	0.967	0.967	0.967
8.0 Hz	1.036	1.036	1.036
16.0 Hz	0.768	0.768	0.768

	Lateral	Fore-and-aft	Vertical
	seat-surface	seat-surface	seat-surface
	Wd	Wd	Wk
0.5 Hz	0.853	0.853	0.418
1.0 Hz	0.992	0.992	0.462
4.0 Hz	0.512	0.512	0.967
8.0 Hz	0.253	0.253	1.036
16.0 Hz	0.125	0.125	0.768

	Lateral	Fore-and-aft	Vertical
	backrest	backrest	backrest
	Wd	Wc	Wd
0.5 Hz	0.853	0.843	0.853
1.0 Hz	0.992	0.991	0.992
4.0 Hz	0.512	1.024	0.512
8.0 Hz	0.253	0.891	0.253
16.0 Hz	0.125	0.512	0.125

Table 3.3 Multiplying factors from ISO 2631 (1997)

	Lateral	Fore-and-aft	Vertical
feet	0.25	0.25	0.4
seat-surface	1.0	1.0	1.0
backrest	0.5	0.8	0.4

The r.m.s. accelerations at the seat-surface and at the backrest were assessed with the r.m.s. vibrator platform acceleration (identical to the r.m.s. acceleration at the feet) and the seat transmissibility. The seat transmissibility was measured at the seat-pan and at the backrest in the fore-and-aft and vertical direction with an 80 kg, 26 year old male subject, with a 0.8 $m.s^{-2}$ r.m.s. broadband random vibration (between 0.2 and 20 Hz). The seat transmissibility was assumed to be 1.0 in the lateral direction. Table 3.4 shows the different transmissibilities of the seat-pan and backrest depending on the frequency and direction of excitation.

The objective of this section is to calculate the r.m.s. accelerations of the vibrator platform (for all sinusoid studied) that generates the same total weighted acceleration as the 4-Hz lateral sinusoid at 0.5 m.s^{-2} r.m.s.

The first step is to calculate the total weighted r.m.s. acceleration of the reference stimulus (a 4-Hz lateral sinusoid at 0.5 m.s^{-2} r.m.s.). The weighted r.m.s. acceleration at one location can be expressed as:

$$a_{\mathrm{wl}ocation} = k_m(k_{wf}(k_{st}.a_{\mathrm{rms}}))$$

where

$a_{\mathrm{wl}ocation}$	is the weighted r.m.s. acceleration at a body location (feet, seat-pan or backrest)
a_{rms}	is the r.m.s. acceleration of the vibrator platform (also the r.m.s. acceleration at the feet)
k_{st}	is the seat transmissibility at the corresponding location, direction and frequency (given by Table 4.4)
k_{wf}	is the frequency weighting factor at the corresponding location, direction and frequency (given by Table 3.2)
k_m	is the multiplying factor at the corresponding location and direction (given by Table 3.3)

According to the weighting factors presented in Tables 3.2, 3.3 and 3.4 the calculation of the total weighted r.m.s. acceleration of the 0.5 ms^{-2} r.m.s. 4-Hz lateral reference stimulus required the following equations:

a_{wfeet} = 0.25*(0.967*(1.0*0.5)) = 0.1209 m.s^{-2} r.m.s.

$a_{wseat\text{-}interface}$ = 1.0*(0.512*(1.0*0.5)) = 0.2560 m.s^{-2} r.m.s.

$a_{wbackrest}$ = 0.5*(0.512*(1.0*0.5)) = 0.1280 m.s^{-2} r.m.s.

$a_{WT} = [0.1209^2 + 0.2560^2 + 0.1280^2]^{1/2}$ = 0.31 m.s^{-2} r.m.s.

Table 3.4 Seat transmissibility measured or assumed with an 80 kg male subject, with a broadband random vibration (between 0.2 and 20 Hz) at 0.8 $m.s^{-2}$ r.m.s.

	Lateral seat-surface	Fore-and-aft seat-surface	Vertical seat-surface
0.5 Hz	1.0	1.0	1.0
1.0 Hz	1.0	1.0	1.1
4.0 Hz	1.0	1.0	1.7
8.0 Hz	1.0	1.0	0.8
16.0 Hz	1.0	1.0	0.8

	Lateral backrest	Fore-and-aft backrest	Vertical backrest
0.5 Hz	1.0	1.0	1.0
1.0 Hz	1.0	1.1	1.0
4.0 Hz	1.0	1.7	1.0
8.0 Hz	1.0	0.5	1.0
16.0 Hz	1.0	0.4	1.0

The total overall weighted r.m.s. acceleration of the reference stimulus is 0.31 $m.s^{-2}$ r.m.s. Therefore the magnitudes of all investigated stimuli should give a similar overall weighted r.m.s. acceleration. The next paragraph shows an example of how the equivalent comfort magnitudes were determined.

Table 3.5 Comparison between experimentally measured equivalent comfort magnitudes and predicted equivalent comfort magnitudes calculated using ISO 2631 (1997)

	Lateral		Fore-and-aft		Vertical	
	4-Hz	1-Hz	4-Hz	1-Hz	4-Hz	1-Hz
Median r.m.s. acceleration of sinusoidal stimuli obtained by magnitude estimation test	0.5 (ref)	0.30	0.23	0.26	0.22	0.44
Median r.m.s. acceleration of narrowband random stimuli obtained by magnitude estimation test	0.45	0.27	0.21	0.25	0.20	0.42
Equivalent comfort magnitudes calculated using ISO 2631 (1997)	0.5 (ref)	0.28	0.21	0.23	0.18	0.46

In this example, the magnitude required (denoted a_{rms}), is the r.m.s. acceleration of a 1-Hz lateral sinusoid (measured at the vibrator platform) that produces a total weighted r.m.s. acceleration of 0.31 m.s^{-2} r.m.s.

a_{wfeet} = 0.25*(0.482*(1.0*a_{rms})) = a_{rms} (0.1205)

$a_{wseat\text{-}interface}$ = 1.0*(0.992*(1.0* a_{rms})) = a_{rms} (0.992)

$a_{wbackrest}$ = 0.5*(0.992*(1.0* a_{rms})) = a_{rms} (0.4960)

$a_{WT} = [a^2_{rms} (0.1205^2 + 0.992^2 + 0.4960^2)]^{1/2}$ = 0.31 m.s^{-2} r.m.s.

This gives a vibrator platform r.m.s. acceleration, a_{WT}, of magnitude 0.28 m.s^{-2} r.m.s.

Table 3.5 gives the equivalent discomfort r.m.s. acceleration magnitudes calculated using the procedure described above. The table also compares the magnitudes obtained with magnitude estimation tests (see Section 3.7.1.1).

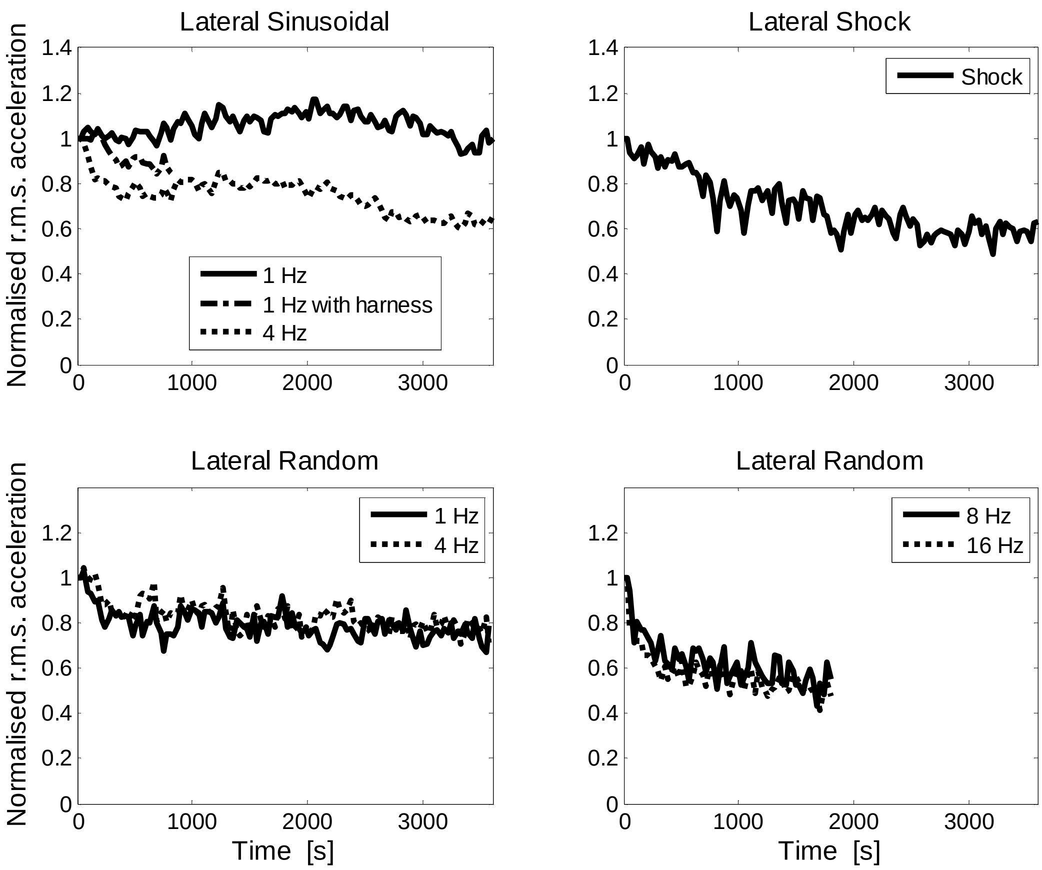


Figure 3.7 Normalised median acceleration measured for 12 subjects in the lateral direction.

Table 3.5 shows that the equivalent discomfort magnitudes obtained with magnitude estimation tests can be reasonably predicted by the standard ISO 2631 (1997). The equivalent discomfort magnitudes of the remaining stimuli used in the subjective studies (0.5 Hz fore-and-aft sinusoid and the 8-Hz and 16-Hz narrowband random stimuli) were determined using the ISO 2631 (1997) according to the procedure previously described.

3.7.2 Lateral excitation

3.7.2.1 Subjective discomfort time-dependencies

Figure 3.7 presents the measured normalized median acceleration of the vibration platform for sinusoidal, narrowband random, and shock motions in the lateral direction.

Figure 3.8 shows the inter-subject variability for all lateral stimuli investigated.

The acceleration curves represent the median vibration magnitudes that produced constant discomfort in the subjects. If subjects decreased the acceleration magnitude with increasing duration so as to feel a constant discomfort, it was assumed that discomfort increased with increasing duration of vibration exposure.

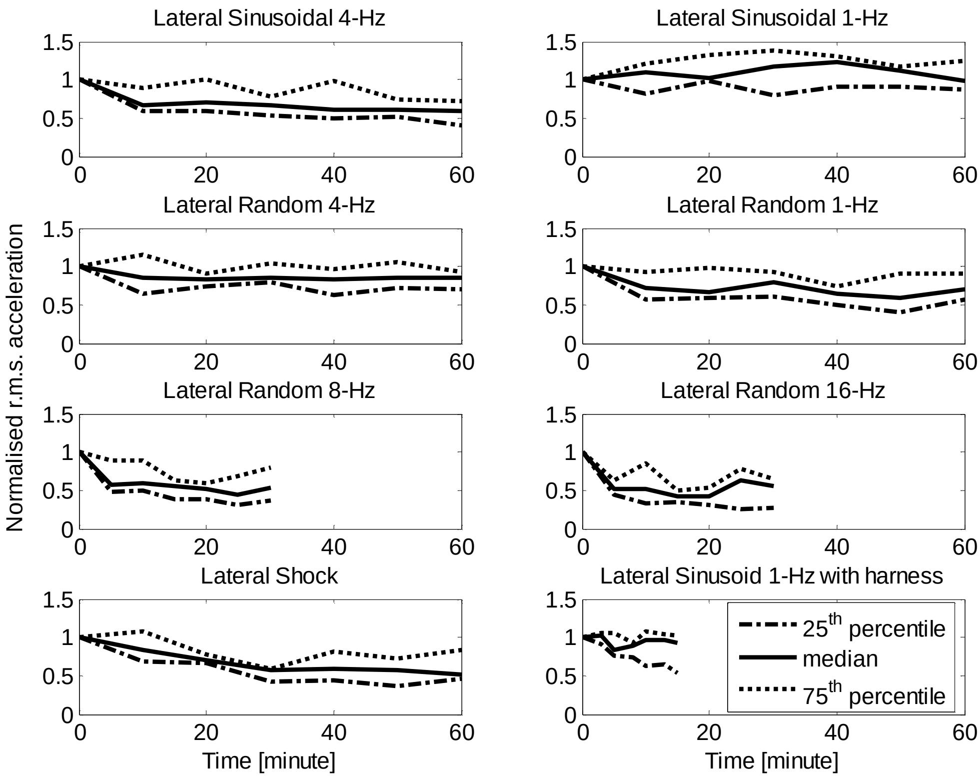


Figure 3.8 Inter-subject variability for lateral stimuli

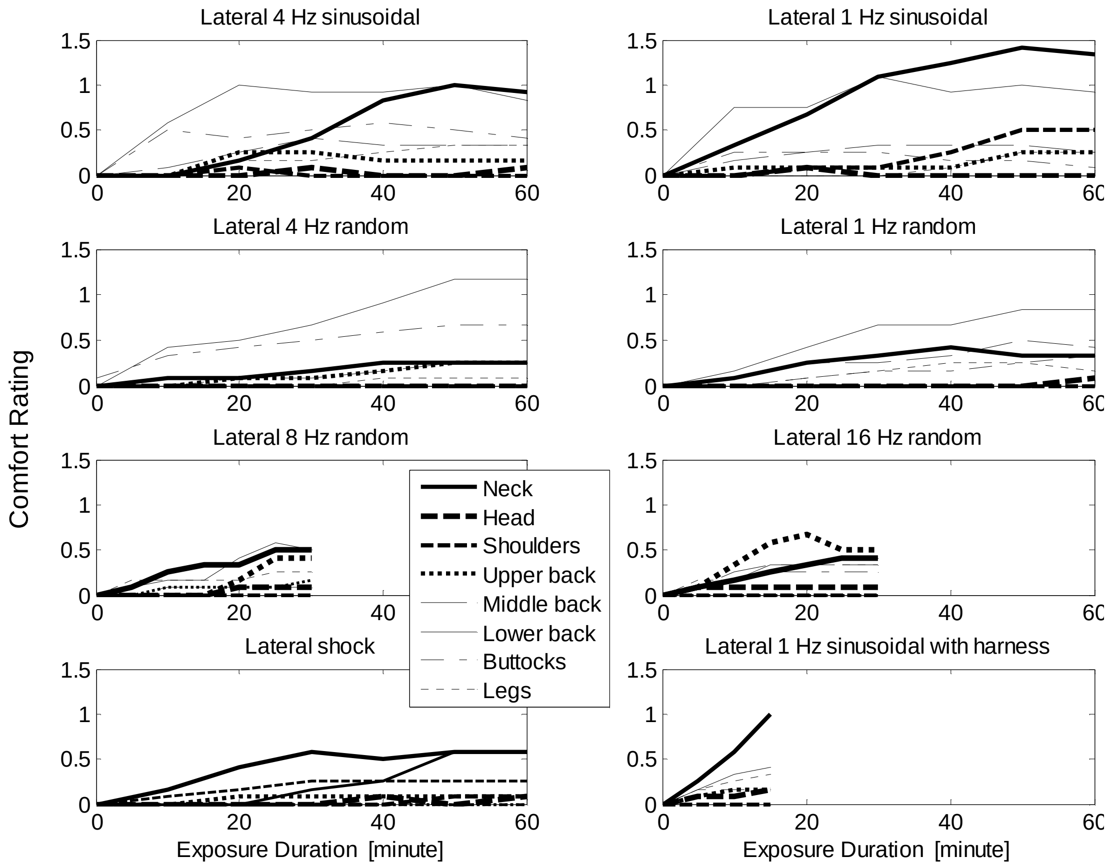


Figure 3.9 Location of discomfort reported every 5 or 10 minutes by the subjects for lateral stimuli.

Statistical analyses have been conducted for each discomfort time-dependency measured to determine the effects of vibration exposure duration on the sensitivity to the vibration magnitude. Data points taken for the analyses were the normalized r.m.s. acceleration for each subject at:

- the beginning, 10^{th}, 30^{th} and 60^{th} minute of exposure for 1-Hz and 4-Hz sinusoidal, narrowband random and shock stimuli,
- the beginning, 10^{th} and 30^{th} minute of exposure for 8-Hz and 16-Hz narrowband random stimuli,
- the beginning and the 15^{th} minute of exposure for 1-Hz lateral sinusoid with harness.

Friedman tests have been performed for each discomfort time-dependency to determine if duration had significant effect on the sensitivity to the vibration magnitude. The level of significance was chosen to be p=0.05. When a significant difference was observed, the

Wilcoxon matched pairs signed rank test for two related samples was used to identify differences between normalised r.m.s. acceleration at two points in time.

All statistical analyses performed are presented in Appendix 1, Section 1.

Friedman tests revealed that vibration exposure duration significantly affected the sensitivity to the vibration magnitude for all stimuli except the 1-Hz lateral sinusoidal stimulus:

- $p = 0.64$ for 1-Hz lateral sinusoidal stimulus,
- $p = 0.003$ for 4-Hz lateral sinusoidal stimulus,
- $p = 0.021$ for 1-Hz lateral narrowband random stimulus,
- $p = 0.042$ for 4-Hz lateral narrowband random stimulus,
- $p = 0.017$ for 8-Hz lateral narrowband random stimulus,
- $p = 0.001$ for 16-Hz lateral narrowband random stimulus,
- $p = 0.003$ for lateral shock stimulus.

Wilcoxon matched pair signed rank test for two related samples showed:

- the SDTS was greater with the 4-point harness than without ($p = 0.042$),
- the sensitivity to the vibration magnitude increased mainly during the first 10 minutes of exposure.

Results showed that the sensitivity to the vibration magnitude increased with vibration exposure duration for most of the stimuli (except 1-Hz lateral sinusoidal stimulus). Also, the SDTD was not the same throughout the exposure duration, subjects decreased the vibration magnitude mainly during the first 10 minutes of exposure.

3.7.2.2 Location of discomfort

Figure 3.9 shows the average ratings of discomfort at locations reported by the subjects during lateral excitation.

The maximum mean discomfort reached a level of 1.2, corresponding to “a little uncomfortable” on the semantic scale. Subjects were asked to keep constant their global discomfort. Discomfort at some body areas could reduce during exposure, whereas discomfort at other body areas could increase.

Statistical analyses were performed to determine if there were some locations, for each condition tested, where discomfort was significantly greater than the rest of the body locations mentioned by the subjects. Within each experimental condition, a Friedman test was used to test whether there was a significant difference ($p<0.05$) across the different locations of discomfort. When the Friedman test revealed a significant difference, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between pairs of conditions.

The location of most discomfort was defined as being the location having a rating of discomfort significantly greater than three or more other locations of discomfort mentioned by the subjects during the session. An example showing how these locations were determined for each condition is given for the 1-Hz sinusoidal lateral vibration. Table 3.6 shows the results of the Freidman test performed with the body locations felt to be uncomfortable by the subjects. The Friedman test showed that some locations had significantly greater discomfort than others. Therefore each combination composed of pairs of locations of discomfort was tested with the Wilcoxon matched-pairs signed ranks test for two related samples. Table 3.7 shows the results of the Wilcoxon tests. Discomfort at the neck was significantly greater than at the middle-back, the buttocks, and the legs. The neck was therefore considered to be the location of most discomfort.

Similar statistical analyses have been performed for each condition. All the results are presented in Appendix 2, Section 1.

Friedman and Wilcoxon tests showed:

Table 3.6 Friedman test performed with locations mentioned as being uncomfortable during prolonged exposure to 1-Hz sinusoidal lateral vibration.
The variables' names are constructed with l: lateral, s: sinusoid, 1: 1Hz then the location. For example 'ls1neck' is the discomfort rating at the neck for lateral (l) sinusoid (s) at 1 Hz (1). (shou: shoulder, uppba: upper-back, midba: middle-back, butt: buttocks)

Ranks

	Mean Rank
ls1neck	5,29
ls1shou	3,71
ls1uppba	3,42
ls1midba	3,67
ls1lowba	5,08
ls1butt	3,38
ls1leg	3,46

Test Statistics[a]

N	12,000
Chi-Square	16,288
df	6,000
Asymp. Sig.	,012

a. Friedman Test

Table 3.7 Results of the Wilcoxon matched-pairs signed ranks test for two related samples obtained with 8-Hz narrowband random fore-and-aft vibration.

Lateral sinusoid 1 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.149	0.096	0.048	0.398	0.016	0.027
Shoulders			0.414	0.680	0.161	0.336	0.496
Upper-back				0.705	0.024	0.705	1.000
Middle-back					0.084	0.414	0.785
Lower-back						0.031	0.087
Buttocks							0.665

- 1-Hz lateral sinusoidal stimulus produced most discomfort at the neck,
- 1-Hz lateral sinusoidal stimulus with harness produced most discomfort at the neck,
- 4-Hz lateral sinusoidal stimulus produced most discomfort at the neck,
- 1-Hz lateral narrowband random stimulus produced most discomfort at the lower-back,
- 4-Hz lateral narrowband random stimulus produced most discomfort at the lower-back,
- 8-Hz lateral narrowband random stimulus produced no location of most discomfort,
- 16-Hz lateral narrowband random stimulus produced no location of most discomfort,
- shock lateral stimulus produced most discomfort at the neck and lower-back.

It seems that prolonged exposure to lateral vibration produced discomfort mainly at the neck and lower-back.

3.7.3 Fore-and-aft excitation

3.7.3.1 Subjective discomfort time-dependencies

Figure 3.10 presents the normalized median acceleration of the vibration platform for sinusoidal, random, and shock motions in the fore-and-aft direction.

Figure 3.11 shows the inter-subject variability for all fore-and-aft stimuli investigated.

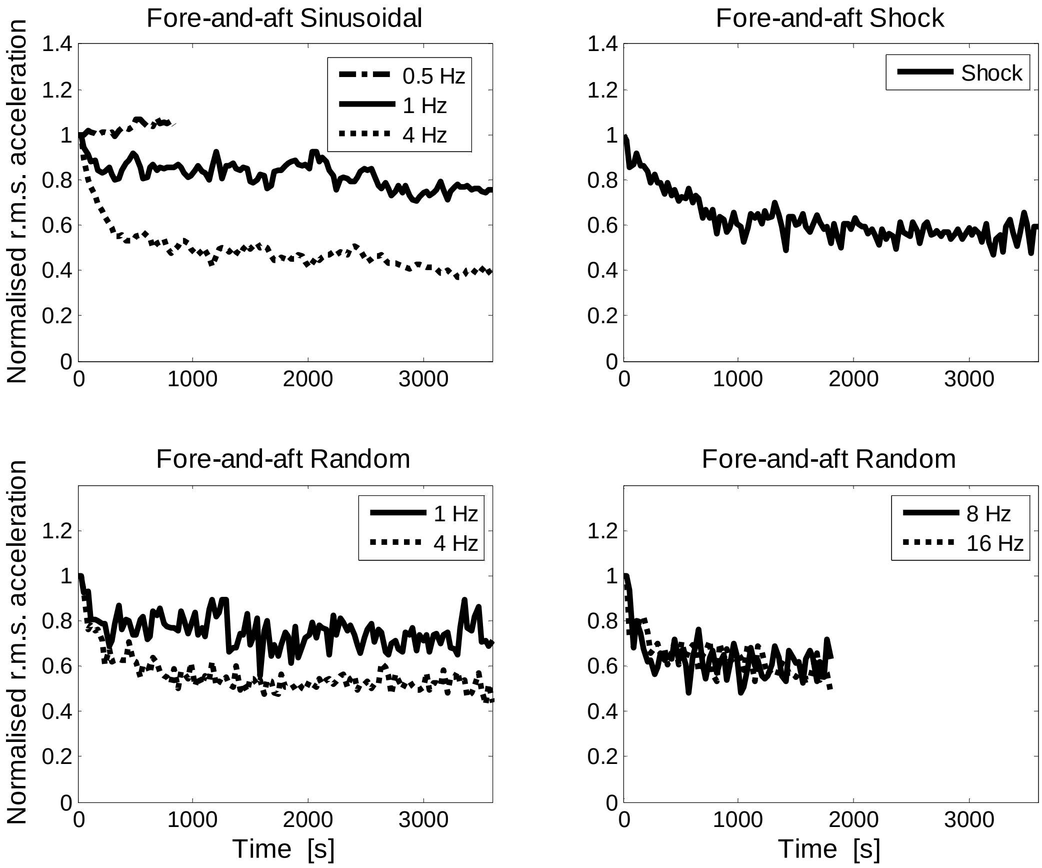


Figure 3.10 Normalised median acceleration measured for 12 subjects in the fore-and-aft direction.

Friedman tests have been performed for each discomfort time-dependency to determine if duration had a significant effect on the sensitivity to the vibration magnitude. The level of significance was chosen to be *p*=0.05. When a significant difference was observed, the Wilcoxon matched pairs signed rank test for two related samples was used to identify differences between normalised r.m.s. acceleration at two points in time.

All statistical analyses performed are presented in Appendix 1, Section 1.

Friedman tests revealed that vibration exposure duration affects significantly the sensitivity to the vibration magnitude for all fore-and-aft stimuli (except for the 0.5-Hz sinusoid):

- *p* = 0.015 for 1-Hz fore-and-aft sinusoidal stimulus,
- *p* = 0.000 for 4-Hz fore-and-aft sinusoidal stimulus,
- *p* = 0.019 for 1-Hz fore-and-aft narrowband random stimulus,
- *p* = 0.000 for 4-Hz fore-and-aft narrowband random stimulus,
- *p* = 0.039 for 8-Hz fore-and-aft narrowband random stimulus,

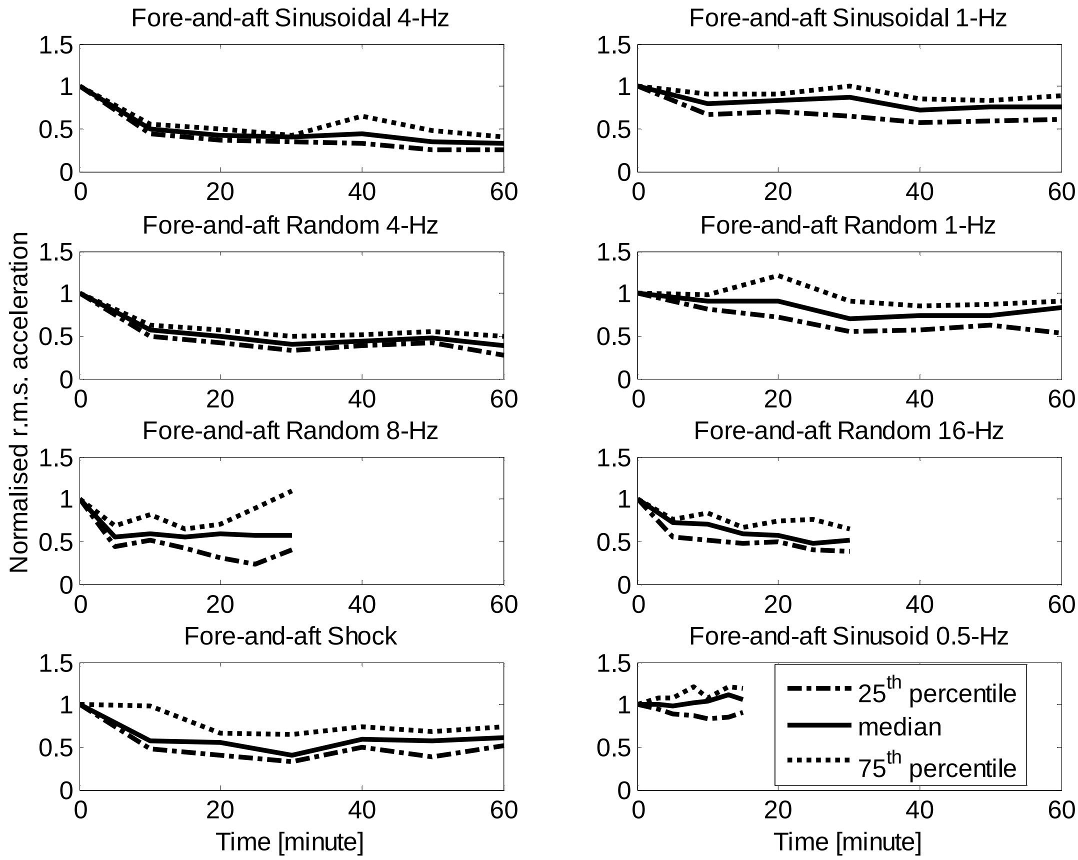


Figure 3.11 Inter-subject variability for fore-and-aft stimuli

- *p* = 0.000 for 16-Hz fore-and-aft narrowband random stimulus,
- *p* = 0.003 for fore-and-aft shock stimulus.

Wilcoxon matched pairs signed rank test for two related samples showed:

- sensitivity to vibration magnitude did not increase during 15 minute of exposure to a 0.5-Hz sinusoidal fore-and-aft stimulus (*p* = 0.17),
- sensitivity to vibration magnitude increased mainly during the first 10 minutes of exposure (see Appendix 1, Section 1).

Results showed that the sensitivity to vibration magnitude increased with vibration exposure duration for most of the stimuli (except 0.5-Hz fore-and-aft sinusoidal stimulus). Also, the SDTD was not the same throughout the exposure duration; subjects decreased the vibration magnitude mainly during the first 10 minutes of exposure.

3.7.3.2 Location of discomfort

Figure 3.12 shows the average ratings of discomfort at locations reported by the subjects during fore-and-aft excitation.

Statistical analyses were performed to determine if they were some locations, for each condition tested, where discomfort was significantly greater than the rest of the body locations mentioned by the subjects. Within each experimental condition, a Friedman test was used to test whether there was a significant difference (p<0.05) across the different locations of discomfort. When the Friedman test revealed a significant difference, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between pairs of conditions.

The locations of most discomfort have been determined as described in Section 3.7.2.2. All the statistical results are presented in Appendix 2, Section1.

The Friedman and Wilcoxon tests showed:

- 0.5-Hz fore-and-aft sinusoidal stimulus produced no location of most discomfort,

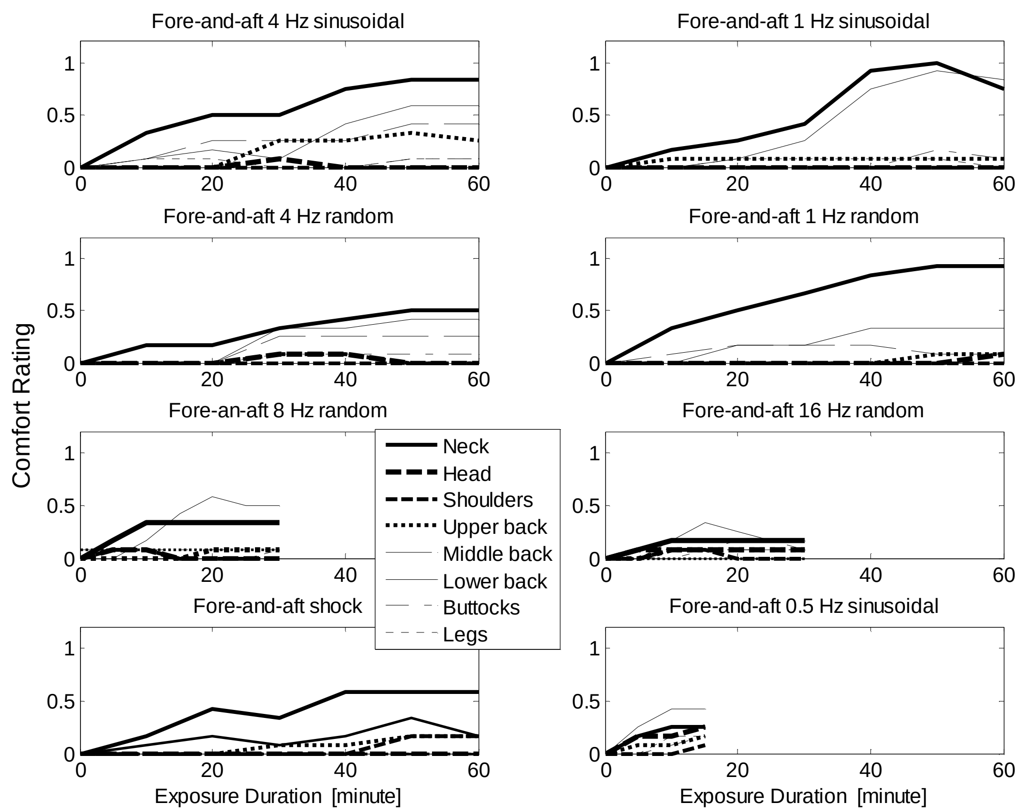


Figure 3.12 Location of discomfort reported every 5 or 10 minutes by the subjects for fore-and-aft stimuli.

- 1-Hz fore-and-aft sinusoidal stimulus produced most discomfort at the neck and the lower-back,
- 4-Hz fore-and-aft sinusoidal stimulus produced most discomfort at the neck,
- 1-Hz fore-and-aft narrowband random stimulus produced most discomfort at the neck and lower-back,
- 4-Hz fore-and-aft narrowband random stimulus produced most discomfort at the neck,
- 8-Hz fore-and-aft narrowband random stimulus produced most discomfort at the lower-back,
- 16-Hz fore-and-aft narrowband random stimulus produced no location of most discomfort,
- shock fore-and-aft stimulus produced most discomfort at the neck.

It seems that prolonged exposure to fore-and-aft vibration produced discomfort mainly at

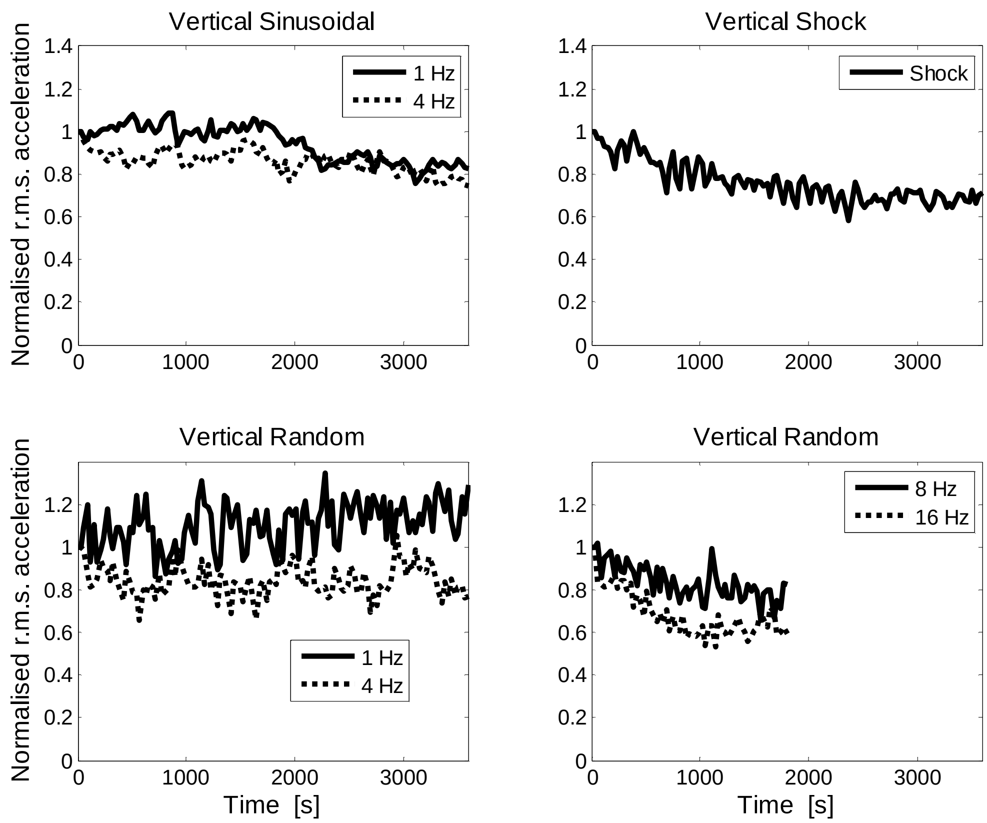


Figure 3.13 Normalised median acceleration measured for 12 subjects in the vertical direction.

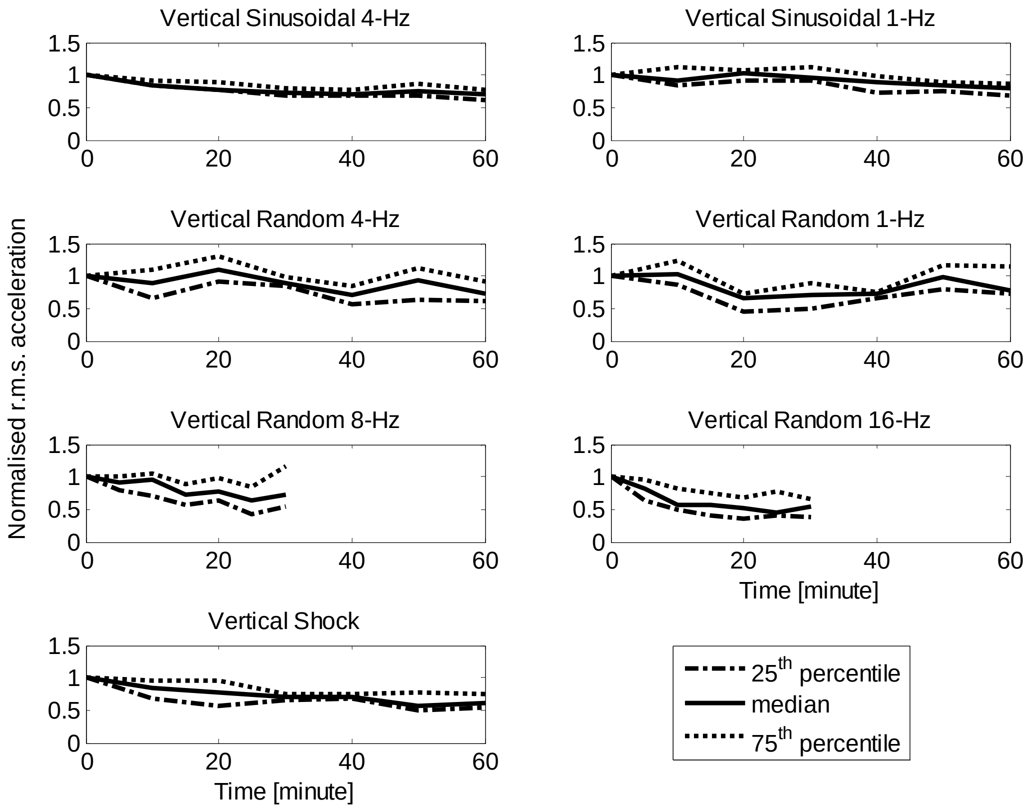


Figure 3.14 Inter-subject variability for vertical stimuli

the neck and lower-back.

3.7.4 Vertical excitation

3.7.4.1 Subjective discomfort time-dependencies

Figure 3.13 presents the normalized median acceleration of the vibration platform for sinusoidal, random and shock motions in the vertical direction.

Figure 3.14 shows the inter-subject variability for all vertical stimuli investigated.

Friedman tests have been performed for each discomfort time-dependency to determine if duration had a significant effect on the sensitivity to vibration magnitude. The level of significance was chosen to be p=0.05. When a significant difference was observed, the Wilcoxon matched pairs signed rank test for two related samples was used to identify differences between normalised r.m.s. acceleration at two points in time.

All statistical analyses performed are presented in Appendix 1, Section 1.

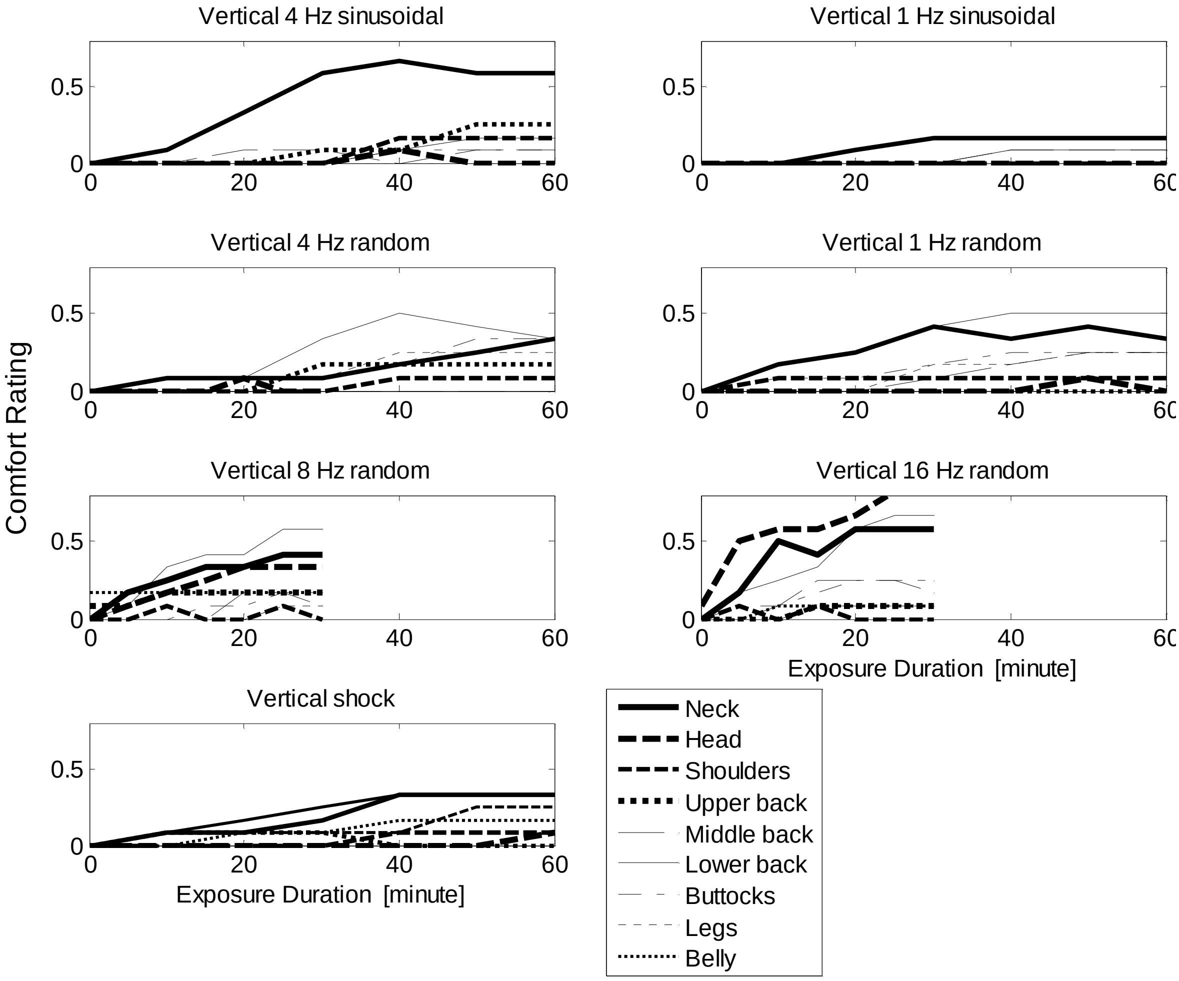


Figure 3.15 Location of discomfort reported every 5 or 10 minutes by the subjects for vertical stimuli.

Friedman tests revealed that vibration exposure duration affects significantly the sensitivity to vibration magnitude for most of vertical stimuli (except 4-Hz and 8-Hz narrowband random vibration):

- *p* = 0.026 for 1-Hz vertical sinusoidal stimulus,
- *p* = 0.000 for 4-Hz vertical sinusoidal stimulus,
- *p* = 0.043 for 1-Hz vertical narrowband random stimulus
- *p* = 0.315 for 4-Hz vertical narrowband random stimulus,
- *p* = 0.558 for 8-Hz vertical narrowband random stimulus,
- *p* = 0.018 for 16-Hz vertical narrowband random stimulus,
- *p* = 0.002 for vertical shock stimulus.

Wilcoxon matched pairs signed rank test for two related samples showed that subjects decreased the vibration magnitude mainly during the first 10 minutes of exposure (see Appendix 1, Section 1).

Results showed that the sensitivity to vibration magnitude increased with vibration exposure duration for most of the stimuli (except 4-Hz and 8-Hz vertical narrowband random stimulus). Also, the SDTD was not the same throughout the exposure duration.

The statistical analysis performed with 1-Hz and 4-Hz narrowband random vertical stimuli should be considered carefully. The discomfort time-dependencies obtained for these conditions show high magnitude variability. It seems that subjects had more difficulty in adjusting vibration magnitude to keep constant their discomfort for these vertical conditions than during the other conditions. Therefore statistical results for 1-Hz and 4-Hz random stimuli could have been different if different data points were taken for analyses.

3.7.4.2 Location of discomfort

Figure 3.15 shows the averaged ratings of discomfort at locations reported by the subjects during vertical excitation.

Statistical analyses were performed to determine if they are some locations, for each condition tested, where discomfort was significantly greater than the rest of the body

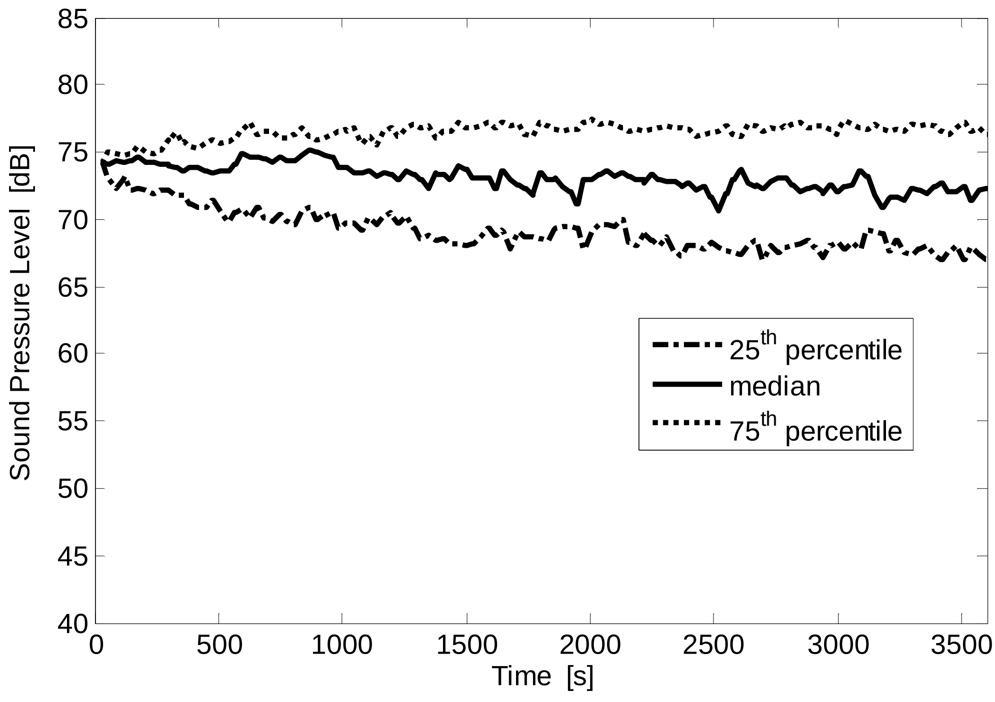


Figure 3.16 Control study: Sound pressure level producing a constant feeling of loudness during one hour exposure to 1000-Hz sinusoid.

locations mentioned by the subjects. Within each experimental condition, a Friedman test was used to test whether there was a significant difference ($p<0.05$) across the different locations of discomfort. When the Friedman test revealed a significant difference, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between pairs of conditions.

The locations of most discomfort have been determined as described in Section 3.7.2.2. All the statistical results are presented in Appendix 2, Section1.

The Friedman and Wilcoxon tests showed:

- 1-Hz vertical sinusoidal stimulus produced no location of most discomfort,
- 4-Hz vertical sinusoidal stimulus produced most discomfort at the neck,
- 1-Hz vertical narrowband random stimulus produced no location of most discomfort,
- 4-Hz vertical narrowband random stimulus produced no location of most discomfort,

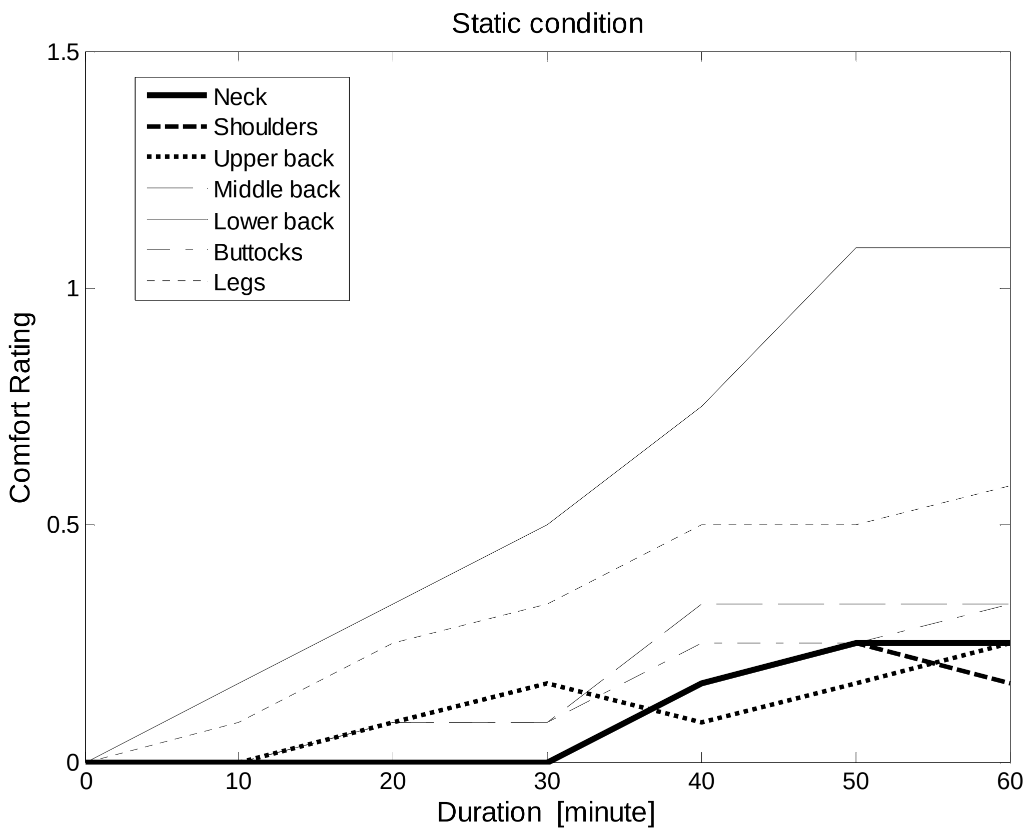


Figure 3.17 Location of discomfort reported every 10 minutes by the subjects during the control condition.

- 8-Hz vertical narrowband random stimulus produced no location of most discomfort,
- 16-Hz vertical narrowband random stimulus produced most discomfort at the head, neck and lower-back,
- shock vertical stimulus produced no location of most discomfort.

Neck and lower-back discomfort seem to be not as important for vertical stimuli than horizontal stimuli. Most of the vertical conditions did not produce most discomfort at the neck or lower-back.

3.7.5 Control condition

During the static condition, subjects were asked to control the level of an acoustic white noise so as to keep the loudness of the sound constant over time. Figure 3.16 shows the median, the 25^{th} and 75^{th} percentile of the sound pressure level measure during the control condition.

The control study was performed to compare the locations and ratings of discomfort at these locations, between the static and the dynamic conditions. It is expected to determine which part of static discomfort is included in the dynamic discomfort measured during prolonged exposure to vibration. Figure 3.17 shows the average rating of discomfort at locations reported by the subjects every 10 minutes.

A Friedman test was used to test whether there was a significant difference ($p<0.05$) across the different locations of discomfort. When the Friedman test revealed a significant difference, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between pairs of conditions.

The locations of most discomfort have been determined as described in Section 3.7.2.2. All the statistical results are presented in Appendix 2, Section1.

The Friedman and Wilcoxon tests showed that the lower-back was the only location of most discomfort during prolonged static posture.

3.7.6 Effects of vibration duration on discomfort time-dependencies

Sections 3.7.2.1, 3.7.3.1 and 3.7.4.1 presented the effects of the vibration exposure duration on the sensitivity to vibration magnitude. All the statistical analyses showing the asymptotic significance of the Friedman and Wilcoxon tests performed are presented in Appendix 1, Section 1.

The results showed that:

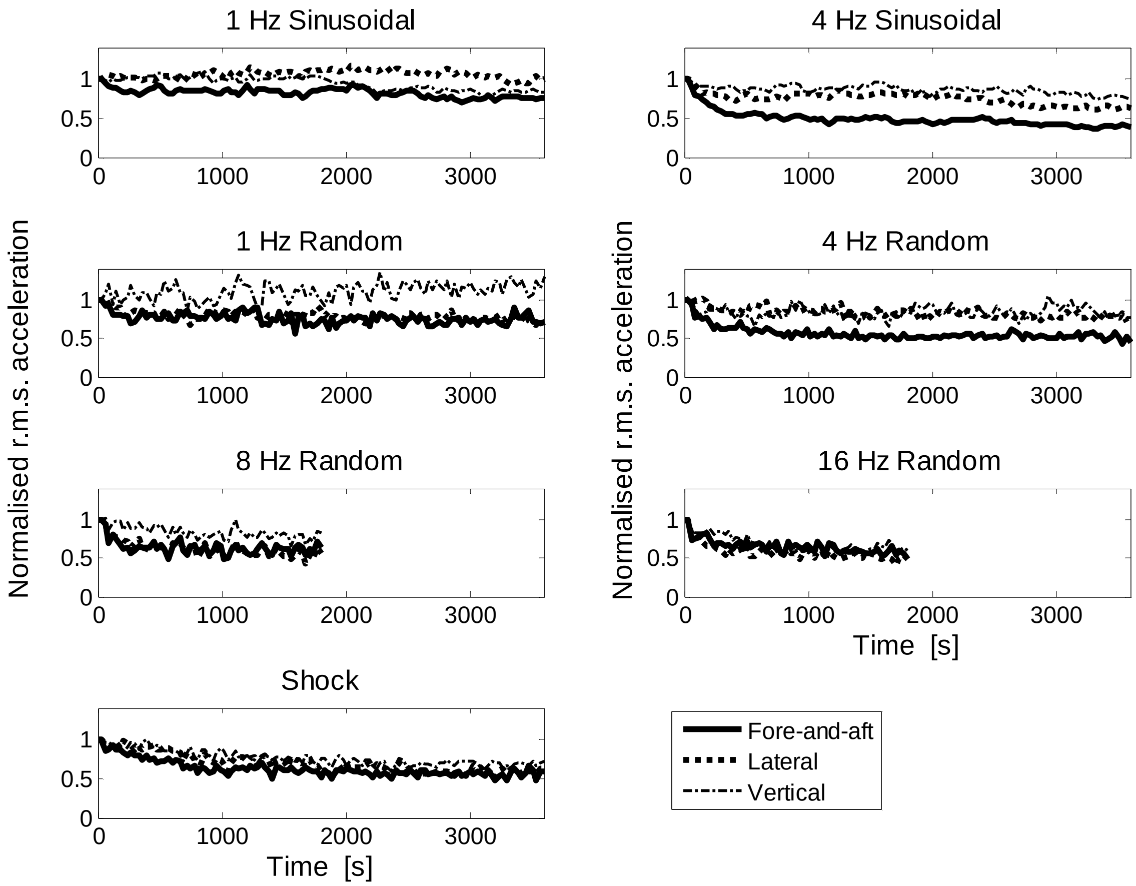


Figure 3.18 Effects of the direction of excitation on the discomfort time-dependency.

- the sensitivity to vibration magnitude increased with increasing vibration exposure duration (except for 0.5-Hz fore-and-aft sinusoidal, 1-Hz lateral sinusoidal, 4-Hz and 8-Hz vertical narrowband random stimuli),

- the sensitivity to vibration magnitude did not increase at the same rate throughout the exposure duration. The sensitivity to vibration magnitude increased mainly during the first 10 minutes of exposure. For most stimuli, the sensitivity does not increase after the 30th minute of vibration exposure.

3.7.7 Effects of direction of excitation on subjective discomfort time-dependencies

Figure 3.18 shows the effects of the direction of excitation on the subjective discomfort time-dependency (SDTD).

Statistical analyses were conducted using the Friedman test to compare effects of the direction of excitation within each frequency and waveform, with data points taken at the

60th minutes of exposure for the sinusoidal stimuli and at the 30th minute of exposure for the 8-Hz and 16-Hz narrowband random stimuli. When a significant difference was observed, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between two directions.

All statistical results performed to investigate the effects of the direction of excitation on the discomfort time-dependency are presented in Appendix 1 Section 2.

The following presents all the significant differences observed with Friedman and Wilcoxon tests:

- 1-Hz sinusoidal fore-and-aft excitation produced significantly greater SDTD than 1-Hz sinusoidal lateral ($p = 0.012$),
- 1-Hz sinusoidal vertical excitation produced significantly greater SDTD than 1-Hz sinusoidal lateral excitation ($p = 0.012$),
- 4-Hz sinusoidal fore-and-aft excitation produced significantly greater SDTD than 4-Hz sinusoidal lateral excitation ($p = 0.048$),
- 4-Hz narrowband random fore-and-aft excitation produced significantly greater SDTD than 4-Hz narrowband random lateral excitation ($p = 0.007$) and vertical excitation ($p = 0.012$).

According to these statistical analyses, it seems that the fore-and-aft stimuli produced greater SDTD that lateral and vertical stimuli, especially for low frequency motions. Possible reasons are discussed in Section 3.8.

3.7.8 Effects of waveform on subjective discomfort time-dependencies

Figure 3.19 shows the effects of the waveform of the excitation on the subjective discomfort time-dependencies (SDTD).

Friedman tests were performed to compare the effects of the waveform of the excitation within each direction studied at 1 Hz, with data points taken at the 60th minutes of exposure. When a significant difference was observed, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between two waveforms. Only the Wilcoxon matched-pairs signed ranks test for two related samples was used for 4 Hz stimuli to compare sinusoidal and random waveforms.

All statistical results are presented in Appendix 1, Section 3.

The waveform of the excitation had a limited effect on the discomfort time-dependency. Only three significant differences due to the waveform were found:

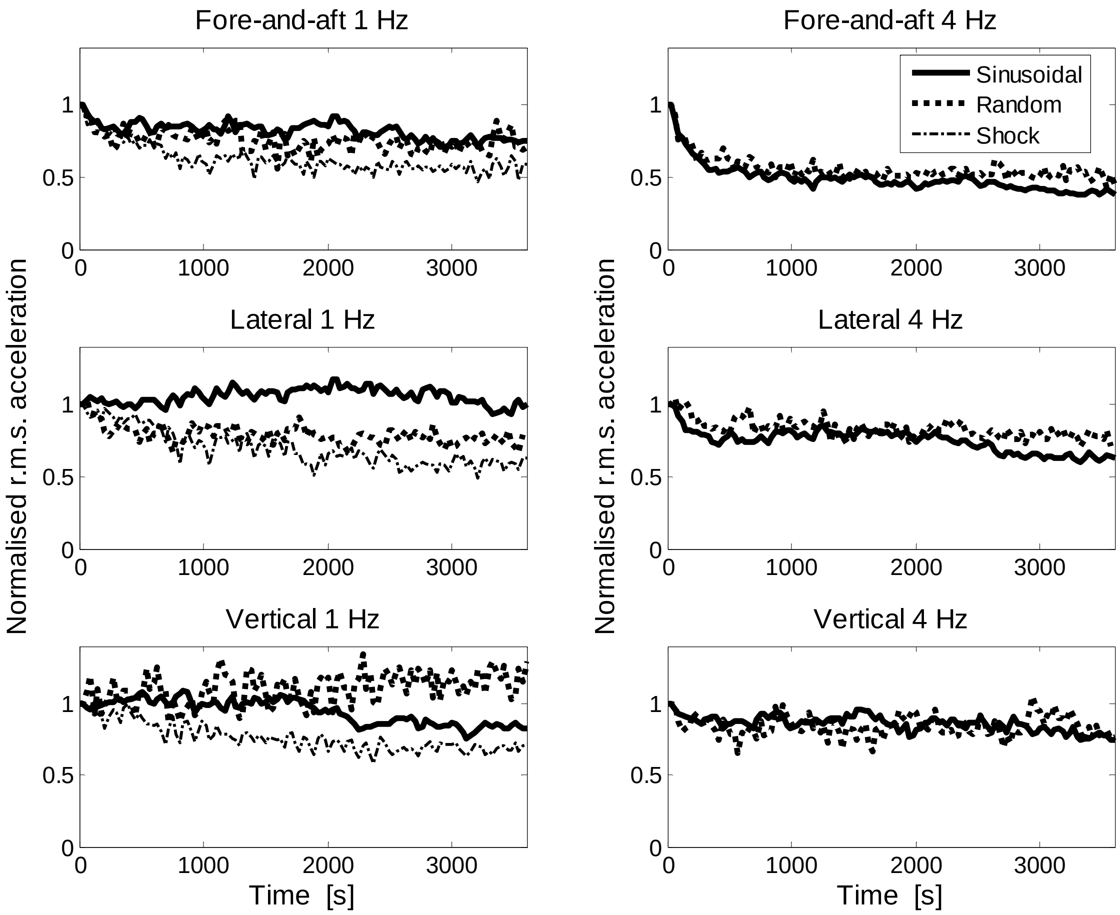


Figure 3.19 Effects of the waveform of excitation on the discomfort time-dependency.

- 1-Hz sinusoidal lateral excitation produced significantly less SDTD than shock stimulus (p = 0.025) and narrowband random stimulus (p = 0.044),
- 1-Hz vertical shock excitation produced significantly greater SDTD than 1-Hz random (p = 0.044).

The waveform of excitation did not affect significantly the discomfort time-dependency for fore-and-aft stimuli.

3.7.9 Effects of frequency on subjective discomfort time-dependencies

Figure 3.20 shows the effects of the frequency of excitation on the subjective discomfort time-dependency (SDTD).

Friedman tests were performed to compare the effect of the frequency of excitation within each direction and waveform studied, with data points taken at the 15th minute of exposure for the 0.5-Hz, 1-Hz and 4-Hz sinusoidal fore-and-aft stimuli, at the 60th minute of

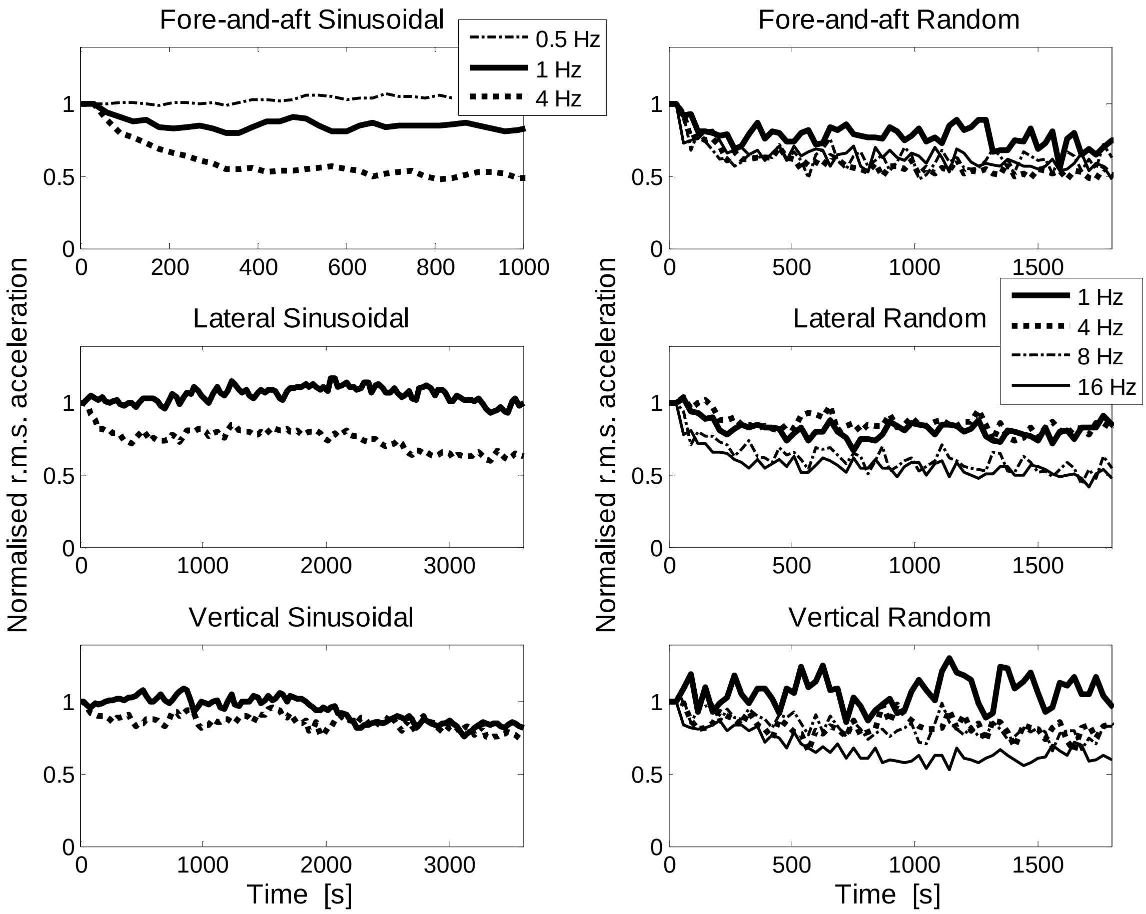


Figure 3.20 Effects of the frequency of excitation on the discomfort time-dependency.

exposure for all the sinusoidal stimuli and at the 30th minute of exposure for the 8-Hz and 16-Hz narrowband random stimuli. When a significant difference was observed, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between two frequencies.

All statistical results are presented in Appendix 1 Section 4. All the significant differences observed with the Friedman and Wilcoxon tests are presented in the following:

- In the fore-and-aft direction, 0.5-Hz sinusoidal excitation produced significantly less SDTD than 1-Hz and 4-Hz sinusoidal excitations (respectively: $p = 0.005$ and $p = 0.005$);
- In the fore-and-aft direction, 1-Hz sinusoidal excitation produced significantly less SDTD than 4-Hz sinusoidal excitation ($p = 0.002$);
- In the fore-and-aft direction, 1-Hz narrowband random excitation produced significantly less SDTD than 4-Hz, 8-Hz and 16-Hz narrowband random

excitations (respectively: p = 0.002, p = 0.043, p = 0.045). No significant differences were found between 4-Hz, 8-Hz and 16-Hz excitations;

- In the lateral direction, 1-Hz sinusoidal excitation produced significantly less SDTD than 4-Hz sinusoidal excitation (p = 0.006);
- In the vertical direction 16-Hz narrowband random excitation produced a significantly greater SDTD than 4-Hz and 8-Hz narrowband random excitations (respectively: p = 0.050, p = 0.023).

Statistical analysis revealed that 1-Hz sinusoidal excitation produced for horizontal directions significantly less SDTD than 4-Hz sinusoidal excitation. For all directions, no significant difference was found between 4-Hz, 8-Hz and 16-Hz narrowband random stimuli (except the 16-Hz vertical stimulus producing more SDTD than 4-Hz and 8-Hz). The effects of frequency of vibration on the discomfort time-dependencies were greatest in the fore-and-aft direction. Statistical analyses showed that SDTD increased with increasing frequency of fore-and-aft sinusoidal stimuli (with 0.5 Hz, 1 Hz and 4 Hz). It was also only in the fore-and-aft direction that the 1-Hz narrowband random stimulus produced significantly SDTD than the 4-Hz narrowband random stimulus. These results are discussed in Section 3.8.

3.7.10 Effects of the body restrain of the subjective discomfort time-dependency

Figure 3.21 shows the effects of the 4-point harness on the subjective discomfort time-dependency (SDTD).

The Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between discomfort time-dependencies produced by a 1-Hz lateral sinusoidal stimulus with and without the 4-point harness (at the 15th minute of exposure). Statistical analyses (presented in Appendix 1, Section 5) showed that the SDTD was greater with the 4-point harness than without (p = 0.039).

A second Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between discomfort time-dependencies produced by a 1-Hz lateral sinusoidal stimulus with the 4-points harness and a 1-Hz fore-and-aft sinusoidal stimulus without harness. Result (presented in Appendix 1, Section 5) shows that the after the 15th minute of exposure the SDTD was not significantly different (p = 0.799).

This result implies that SDTD may also be depending on the body support or restraint. These results are discussed in Section 3.8.

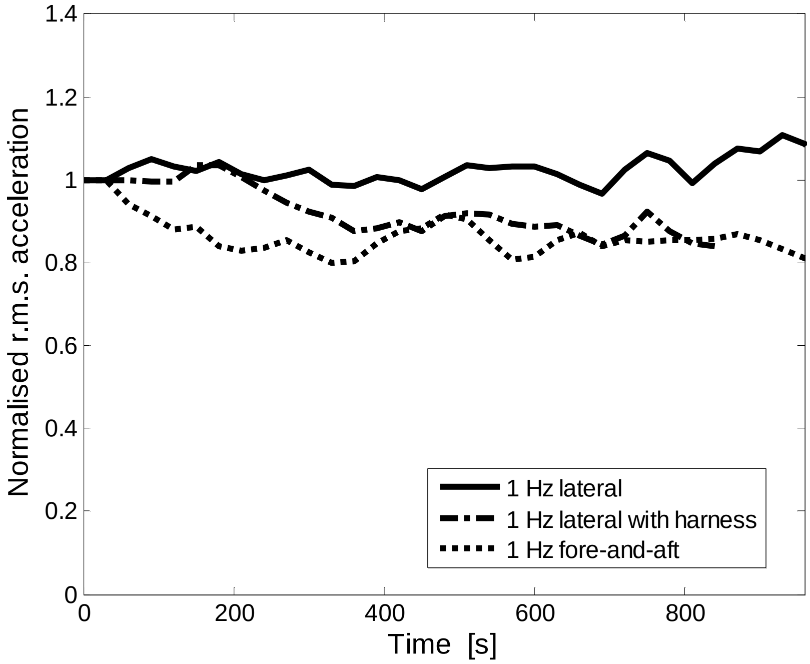


Figure 3.21 Effects of the body support on the discomfort time-dependency.

3.7.11 Effects of prolonged vibration exposure on the location of discomfort

3.7.11.1 Introduction

During prolonged exposure to vibration, discomfort can arise at various locations on the body. The body locations where discomfort is felt may vary with the vibration characteristics (direction, waveform, frequency, magnitude) and with the duration of exposure. The level of discomfort experienced at each location may also vary. Figures 3.9, 3.12, 3.15 and 3.17 show where discomfort was felt and how discomfort evolved with exposure duration. The subjects' task was to keep constant the discomfort, so that it was the same as experienced during the first 10 seconds of exposure, by adjusting the magnitude of the vibration. Subjects may have controlled the increase of discomfort for the body locations that contributed the most to the global discomfort. Therefore the results presented in Figures 3.9, 3.12, 3.15 and 3.17 may have been different if subjects were not required to adjust the magnitude of the vibration.

Some body locations may present levels of discomfort significantly greater than for the other body locations. In the context of this study, this could have several explanations:

- Discomfort felt at these locations may be due to prolonged static posture. In which case, decreasing the magnitude of excitation would not decrease the discomfort.

- Discomfort may increase at specific locations, whereas discomfort is reduced for other body locations.

This section reviews the statistical results obtained to establish the locations of most discomfort. It then presents the relationship between prolonged static posture and its effects on the locations of discomfort experienced during prolonged exposure to vibration. In a third part, the effects of the vibration characteristics on the locations of most discomfort are described.

3.7.11.2 Locations of most discomfort

The location of most discomfort was defined as being the location having a rating of discomfort significantly greater than three or more other locations of discomfort mentioned by the subjects during the session.

Sections 3.7.2.2, 3.7.3.2, 3.7.4.2 and 3.7.5 described the analyses performed and the results obtained (all statistical results are presented in Appendix 2, Section 1). Table 3.8 presents, for all the conditions investigated the locations of most discomfort. For the dynamic conditions, the results showed that the locations of most discomfort were the lower-back and the neck. For the static condition, the lower-back is the only location of most discomfort.

3.7.11.3 Effects of prolonged static posture on the location of discomfort arising during prolonged exposure to vibration

The lower-back was found to be the location of most discomfort for dynamic and static conditions, whereas discomfort at the neck was mostly observed for dynamic studies (see Sections 3.7.2.2, 3.7.3.2, 3.7.4.2 and 3.7.5 and Appendix 2, Section 1).

The Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between a dynamic condition and the static condition using pair of data at the same point in time (same duration).

All statistical results are presented in Appendix 2, Section 2.

Results of the statistical analysis showed that discomfort at the lower-back measured during the static study was not significantly different from most of the dynamic studies. Only three significant differences were found at the lower-back between static and dynamic studies:

- Discomfort at the lower-back was significantly greater during the static study than during prolonged exposure to 1-Hz and 4-Hz sinusoidal vertical stimuli ($p = 0.024$ and $p = 0.02$),

Table 3.8 Locations of most discomfort for all conditions

	Lateral	Fore-and-aft	Vertical
0.5 Hz sinusoid		No location	
1.0 Hz sinusoid	Neck	Neck + Lower-back	No location
1.0 Hz sinusoid with harness	Neck		
4.0 Hz sinusoid	Neck	Neck	Neck
1.0 Hz random	Lower-back	Neck + Lower-back	No location
4.0 Hz random	Lower-back	Neck	No location
8.0 Hz random	No location	Lower-back	No location
16.0 Hz random	No location	No location	Head + Neck + Lower-back
Shocks	Neck + Lower-back	Neck	No location
Static	Lower-back		

- Discomfort at the lower-back was significantly greater during the static study than during prolonged exposure to fore-and-aft shock stimuli ($p = 0.014$).

Similar statistical analysis to that performed with the lower-back was conducted for the discomfort ratings at the neck. A total of eight significant differences were found at the neck between static and dynamic studies:

- Discomfort at the neck was significantly greater during prolonged exposure to 16-Hz narrowband random and 4-Hz sinusoidal vertical stimuli than during prolonged static posture (respectively: $p = 0.049$ and $p = 0.046$),
- Discomfort at the neck was significantly greater during prolonged exposure to 1-Hz and 4-Hz sinusoidal fore-and-aft stimuli than during prolonged static posture ($p = 0.014$ and $p = 0.008$),
- Discomfort at the neck was significantly greater during prolonged exposure to 1-Hz narrowband random fore-and-aft stimuli than during prolonged static posture ($p = 0.023$),

- Discomfort at the neck was significantly greater during prolonged exposure to 1-Hz and 4-Hz sinusoidal lateral stimuli than during prolonged static posture (p = 0.049 and p = 0.039),
- Discomfort at the neck was significantly greater during prolonged exposure to 1-Hz sinusoidal lateral stimuli, with subjects wearing a 4-points harness, than during prolonged static posture (p = 0.038).

The statistical analyses performed suggest that the discomfort felt at the lower-back during prolonged exposure to vibration may have been due to prolonged static posture, whereas discomfort at the neck was more probably due to prolonged exposure to vibration than prolonged static posture.

To keep constant the general level of discomfort, subjects may have reduced the magnitude of the excitation to reduce discomfort at the lower-back. Discomfort at the lower-back was lower for some stimuli than after prolonged static posture. This result may imply that some vibration could help reduce the lower-back discomfort produced by prolonged static posture. Neck discomfort was greater during the dynamic conditions than the static condition. It is therefore more probable that neck discomfort felt during the dynamic studies is due to prolonged exposure to vibration.

3.7.11.4 Effects of the vibration characteristics on the rating of neck discomfort

Friedman tests were performed using various combinations of discomfort ratings at the neck to test for any significant effects of the direction, waveform and frequency of the vibration on the neck discomfort. When the Friedman test revealed a significant difference, the Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between pairs of conditions. All tests performed used data points taken at the same point in time (same duration). All statistical results are presented in Appendix 2, Section 3, 4, 5 and 6.

The effects of the direction of excitation were mainly observed for 1-Hz stimuli. A total of five significant differences were found at the neck between lateral, fore-and-aft and vertical studies:

- Discomfort at the neck was significantly greater after prolonged exposure to the 1-Hz sinusoidal stimulus in the lateral direction than in the fore-and-aft and vertical direction (respectively p = 0.047 and p = 0.034),
- Discomfort at the neck was significantly greater after prolonged exposure to the 1-Hz sinusoidal stimulus in the fore-and-aft direction than in the vertical direction (p = 0.046),

- Discomfort at the neck was significantly greater after prolonged exposure to the 1-Hz narrowband random stimulus in the fore-and-aft direction than in the lateral direction (p = 0.05),
- Discomfort at the neck was significantly greater after prolonged exposure to the 16-Hz narrowband random stimulus in the vertical direction than in the fore-and-aft direction (p = 0.034).

The waveform of the vibration had significant effects on the neck discomfort only in the lateral direction:

- Discomfort at the neck was significantly greater after prolonged exposure to the 4-Hz sinusoidal lateral stimulus than the 4-Hz narrowband random lateral stimulus (p = 0.026),
- Discomfort at the neck was significantly greater after prolonged exposure to the 1-Hz sinusoidal lateral stimulus than the 1-Hz shock lateral stimulus (p = 0.038).

The frequency of excitation had no significant effect on the neck discomfort (see Appendix 2, Section 5).

The duration of the vibration exposure was shortened for some of the stimuli because results have shown that the sensitivity to vibration magnitude increased mainly during the first 10-minutes of exposure (see Section 3.7.6). However the ratings of discomfort at the neck increased during the total duration. Therefore more significant differences could have been found if the duration of all stimuli has been increased to 1-hour.

According to the statistical analyses performed using the ratings of discomfort at the neck, most of the significant differences observed involved the 1-Hz stimuli, especially for horizontal sinusoidal stimuli. It seems that fore-and-aft and lateral sinusoids at 1-Hz produced more discomfort at the neck than other stimuli.

3.7.11.5 Effects of the body restraint on the rating of discomfort at the neck

The effects of the body restraint on the locations and ratings of discomfort were investigated with a 1-Hz lateral sinusoid. The Wilcoxon matched-pairs signed ranks test for two related samples was used to identify differences between the discomfort ratings at the neck measured with and without a 4-point harness.

Result (see Appendix 2, Section 6) showed that discomfort at the neck was significantly greater with subjects wearing the 4-points harness (p = 0.046).

3.8 DISCUSSION

3.8.1 Possible effects of the subjects' environment on the subjective discomfot time-dependencies results

As described in Section 3.6 and in Table 1.1, three main types of environments were used during the various subjective trials:

- subjects wearing blindfold and headphone producing white-noise,
- subjects being inside a cabin without blindfold and headphone,
- subjects being not in a cabin, not wearing blindfold and headphone.

To avoid any acoustical and visual clues that could affect the judgment of the subjects during their tasks (i.e. adjusting the magnitude of the vibration input stimulus to keep constant the level of discomfort at the same level as experienced during the first 10 seconds of exposure), headphones and blindfold were first used. The cabin replaced the headphones and blindfold because three subjects (out of the 12 subjects who participated in the study) told the experimenter, that after the 30th minute of exposure, they felt sleepy. The experimenter, during preliminary sessions with the cabin, made sure that subjects could not hear the changes of stimulus' magnitudes. For the higher frequencies, at 8-Hz and 16-Hz, subjects were not wearing any headphone and blindfold, the cabin was not used. For these sessions, the experimenter verified during preliminary tests that subjects could not hear the changes of the stimulus' magnitudes. In each environmental condition subjects had no separate visual or acoustical clues to adjust the magnitude of the stimuli. Blindfold and headphones were used only for the lateral excitations at 1-Hz, 4-Hz and for shocks. For the same stimuli, in the fore-and-aft and vertical direction, a cabin was mounted on the platform and subjects did not wear headphones or blindfolds. The use of headphones and the corresponding exposure to white noise, for the lateral sessions concerned, may have increased the discomfort experienced by the subjects. It is probable that the discomfort, which may have been produced by the headphones, is uncoupled with discomfort produced by the prolonged exposure to whole-body vibration. Therefore the adjusted vibration amplitude should not be affected greatly by the use of headphones. The blindfold may have increased the sleepiness of the subjects after the 30th minute (as mentioned by 3 subjects). This may have result in a reduced performance of the subjects, when asked to adjust the magnitude of vibration to keep constant their global level of discomfort. Subjective results showed, for almost all stimuli studied, that subjects reduced the vibration magnitude mainly during the first 15 minutes of exposure. The critical results are obtained during these first 15 minutes of exposure, during which there was no evidence that the blindfold had any effect on the subjects' performance.

The main difference between using a cabin and not using the cabin is the visual environment of the subjects. The cabin was not used at 8-Hz and 16-Hz, because at these frequencies subjects could not perceive visual and acoustical clues of the amplitude of the motions (this was verified during preliminary tests as mentioned above). With or without the cabin, subjects were asked to look in front of them. A fractal image was placed in front of them for each situation to limit the possible effect of the environment.

3.8.2 Location of discomfort due to prolonged exposure to vibration

Although subjects were required to adjust the magnitude of the vibration to keep constant their global level of discomfort, Figures 3.9, 3.12 and 3.15 show that for some body locations discomfort increased with vibration duration. The increase of discomfort at these body locations could have two explanations (as stated in Section 3.7.11.1):

- Discomfort at these locations are produced by prolonged static posture, therefore reducing the vibration magnitude will not reduce discomfort.
- Discomfort increased at specific locations whereas it reduces at other locations, maintaining the level of global discomfort constant.

The mean discomfort at these locations was not greater than 1.2 and generally between 0.5 and 1, which according to the semantic scale used corresponds to approximately "a little uncomfortable". For some stimuli the discomfort time-dependencies showed that the median normalised r.m.s. vibration magnitude was halved after the 15th minute of exposure (meaning that the discomfort doubled). According to the levels of discomfort and the comfort time-dependencies obtained in these subjective studies, it is concluded that static discomfort was low enough to be able to measure dynamic discomfort. The combination of discomfort ratings and comfort time-dependencies measured also suggests that subjects adjusted the vibration magnitude to keep their discomfort constant.

Previous studies (see Chapter 2, Section 2.6) have shown that the discomfort of seated subjects during prolonged exposure to vibration can arise at the neck, lower-back or the buttocks (Maeda *et al.,* 2003; Ravnik, 2004). The present subjective studies have also shown that the neck and the lower-back were the main locations of discomfort.

Some epidemiological studies (Magora, 1972; Kelsey, 1975) and other experimental studies (Anderson, 1974; Wikström *et al.* 1994) have found that prolonged static seating could cause lower back discomfort. Statistical analyses showed that the ratings of discomfort at the lower-back during the static studies were not significantly different from ratings during most of the dynamic studies (see Section 3.7.11.3). For some stimuli it even seems that vibration reduces discomfort at the lower back. This suggests that lower-back discomfort was more due to a prolonged static posture than exposure to vibration.

Neck discomfort was significantly greater when subjects were exposed to prolonged vibration than when seated without vibration (see Section 3.7.11.3). This suggests that neck discomfort was more probably due to prolonged exposure to vibration rather than prolonged static posture.

While exposed to vibration the subjects could use the seat backrest and the footrest to maintain their trunk and legs stable. The head was the only body-part that did not have any support and was the body-part most exposed to vibration. The neck muscles, that link the head to the trunk, will be solicited to control head motions during whole-body vibration.

Prolonged exposure to vibration means prolonged neck muscle activation and this might generate 'muscle fatigue' and an increase of discomfort with increasing vibration duration.

3.8.3 Effects of the direction of excitation on the subjective discomfort time-dependency

The neck was the location of most discomfort for six of the fore-and-aft conditions, for four of the lateral conditions and for only two conditions with vertical excitation (see Table 3.8). Section 3.7.7 showed that the SDTD tended to be greater for fore-and-excitation than lateral and vertical excitation. This may suggest that load on the neck used to control head motions depends on the direction of excitation.

To control head motions, muscles other than the neck muscles can be involved. Vibrations are transmitted from the seat to the head through the trunk. The load on the neck muscles could be reduced if the trunk can attenuate some of the vibrations transmitted to the head (like a spring and damper system). The capability of the trunk to reduce load at the neck and therefore discomfort at the neck may depend on the direction of excitation. The backrest offers different body support depending on the direction of the excitation. The backrest restricts body motions of the trunk in the fore-and-aft direction. In the lateral direction, motion of the trunk is restricted only by friction forces between the back and the backrest (and the lateral backrest-support that depends on the type of seat). In the vertical direction, the seat does not greatly restrain the trunk from moving. Seat-to-head transmissibility measurements have been conducted in the three directions with and without backrest by Paddan and Griffin (1988). (The seat-to-head transmissibility represents how vibrations are transmitted from the seat-pan to the head, see Chapter 7.) Their results, presented in Figure 3.21(a), (b) and (c), showed that vibrations are more easily transmitted from the seat-pan to the head with fore-and-aft excitation than with lateral or vertical excitation (for most of the frequency range studied: 0.5 Hz to 16 Hz).

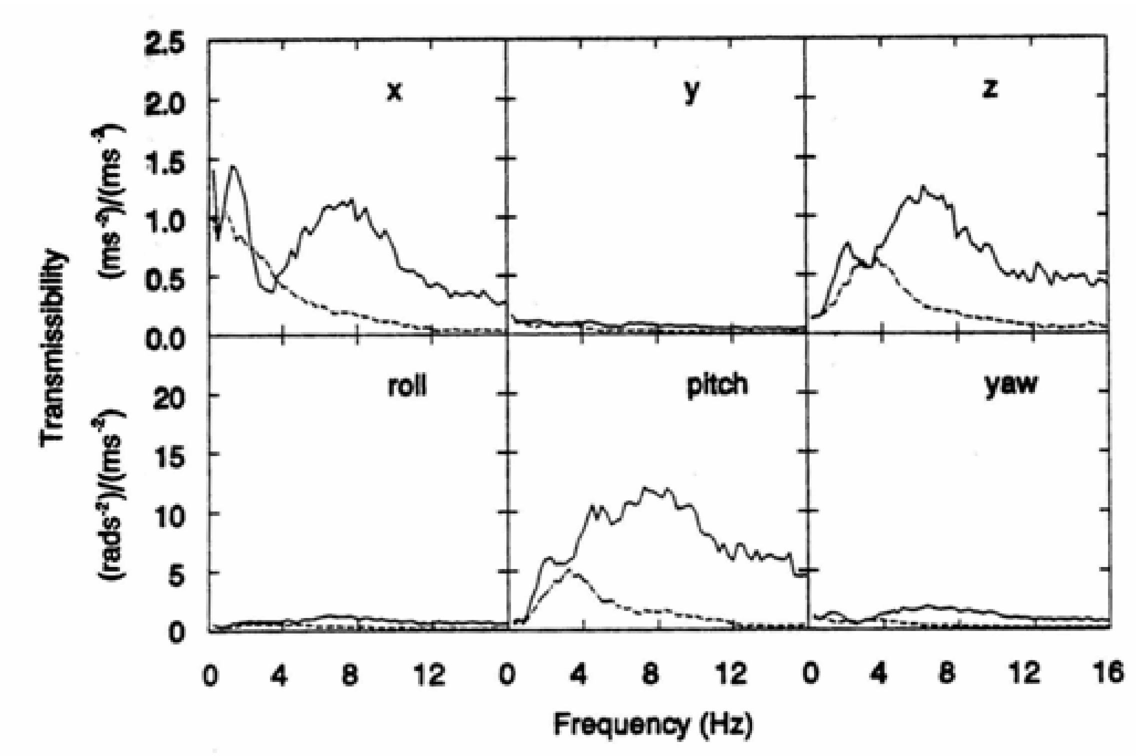


Figure 3.21 (a) Median seat-to-head transmissibility for 12 subjects in back on (-plain curve) and back off (-- dashed curve) posture during fore-and-aft seat vibration (from Paddan and Griffin, 1988).

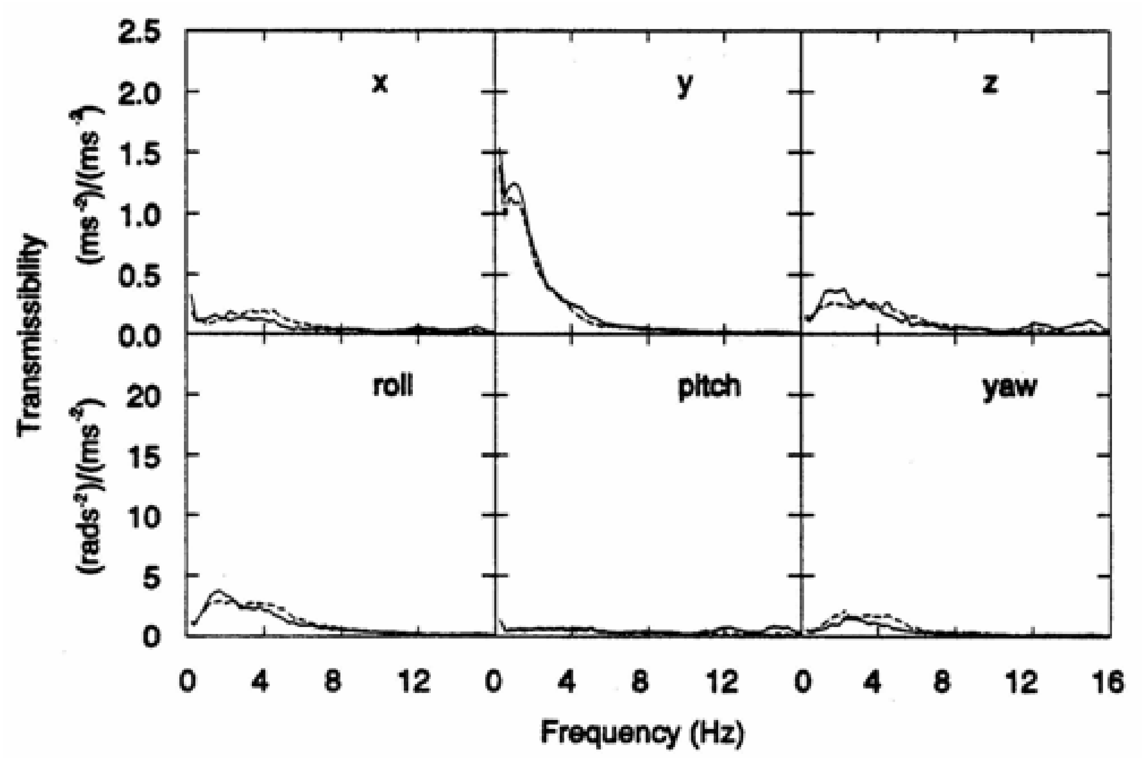


Figure 3.21 (b) Median seat-to-head transmissibility for 12 subjects in back on (-plain curve) and back off (-- dashed curve) posture during lateral seat vibration (from Paddan and Griffin, 1988).

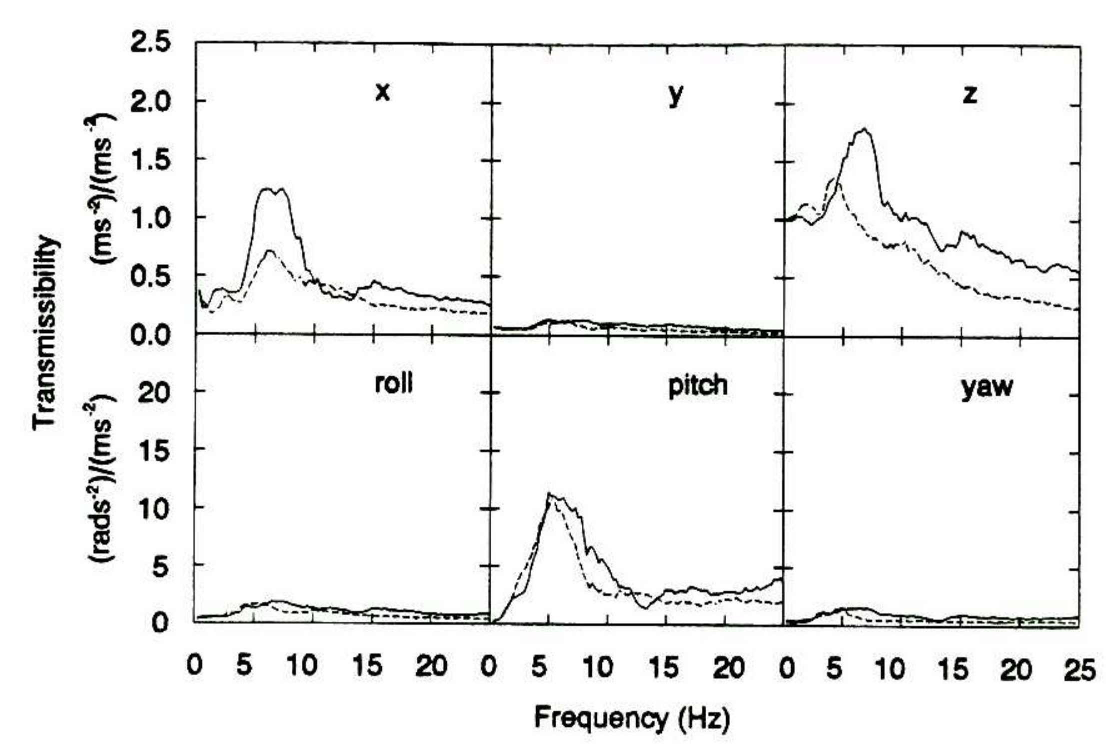


Figure 3.21 (c) Median seat-to-head transmissibility for 12 subjects in back on (-plain curve) and back off (-- dashed curve) posture during vertical seat vibration (from Paddan and Griffin, 1988).

Lateral vibrations were greatly attenuated when reaching the head (from 2 Hz to 16 Hz). Seat-to-head transmissibility for vertical excitations showed a resonance around 5 Hz. Their study also showed the critical effect of a backrest on the transmission of vibration from the seat-pan to the head. The backrest increased greatly the seat-to-head transmissibility for fore-and-aft excitations (for most of the frequency range studied), but had almost no effect for lateral excitation. For vertical excitation, the backrest affected the seat-to-head transmissibility only around 5 Hz. These results tend to confirm the effects of the backrest and the direction of excitation on the ability of the trunk to attenuate the vibration transmitted from the seat-pan to the head. Due to the backrest, the trunk may not be able to reduce the load put on the neck muscles during fore-and-aft vibration exposure. This could explain the effects of vibration direction on the discomfort time-dependency.

3.8.4 Effects of body restrain on the subjective discomfort time-dependency

The 1-Hz lateral sinusoidal study, requiring subjects to wear a 4-point harness, was conducted to investigate the effects of restraining the trunk on the SDTD. The results showed that SDTD was significantly greater with subjects wearing the harness than without wearing the harness (see Section 3.7.10). The harness restrained the lateral trunk motions as the backrest did for fore-and-aft motions. Statistical analysis showed that prolonged exposure to the 1-Hz fore-and-aft sinusoid and the 1-Hz lateral sinusoid with harness gave similar SDTD. These results tend to confirm what was stated in Section 3.8.2. Restricting the trunk to move reduces its ability to attenuate vibration transmitted to the head. The neck muscles are more solicited and discomfort may increase with exposure duration.

3.8.5 Effects of the frequency and waveform of excitation on the subjective discomfort time-dependency

The SDTD was significantly lower with 1-Hz vibration than at higher frequencies and especially for sinusoidal stimuli. Subjects can better anticipate low frequency sinusoidal motions than random and high frequency stimuli. They could use the predictability of the vibration to adopt specific body motion mechanisms (voluntary or involuntary), such as periodical out-of-phase trunk motions, or an anticipated head motion to reduce load on their neck muscles and slow down the increase of discomfort. The anticipation of the vibration could explain the effects of frequency on discomfort-time dependencies.

Anticipation of the motion should be better for sinusoidal stimuli than narrowband random vibrations and therefore greater SDTD are expected for random stimuli than sinusoidal stimuli. However, except for the 1-Hz lateral stimuli, the waveform of excitation had almost no effect on the subjective discomfort time-dependencies. This means that anticipation, predictability, of the vibration cannot explain totally the effects of frequency on SDTD.

The type and/or quantity of neck muscle activity used to control the head motions may depend on the frequency of excitation. It could be hypothesised that different frequencies of excitation produce different types and/or quantity of muscle activities, which also generate different SDTD.

3.8.6 Possible mechanisms responsible of the subjective discomfort time-dependency

Vibrations are perceived through various sensors: vision, vestibular system and somatosensory systems (including the proprioceptive system). Vision provides information of the relative position of the head with respect to the environment; it can detect low frequency motions. The vestibular system, localized in the inner ear, responds to angular and linear acceleration of the head in an earth-fixed referential. The somatosensory system with cutaneous and subcutaneous mechanoreceptors is specialized to detect tactile information. The proprioceptive *(kinaesthetic)* system is responsible for detecting the relative orientations of body segments with respect to each other. Different types of mechanoreceptors exist and each type responds to vibration at different frequency ranges.

However it is not known which particular sensors are responsible for the perception of discomfort. It could be hypothesized that various mechanisms may sense and convey information of discomfort as parts of the visceral system (that could be associated with the somatosensory system) and the skin (associated with the cutaneous and subcutaneous mechanoreceptors). Vibration discomfort could also be related to bones, joints, cartilage and muscles.

The discomfort time-dependency is one aspect of perceiving discomfort. However if the sensors responsible for the perception of particular types of discomfort are not fully understood, the mechanisms responsible for the evolution of discomfort with vibration exposure duration are even more obscure.

The following result obtained from the subjective experiments suggests that discomfort felt at the neck may be one of the components responsible for the measured subjective discomfort time-dependencies (SDTD) for vibration inputs transmitted through a seat:

- During prolonged exposure to vibration, discomfort is felt at the neck and lower-back. Discomfort at the neck appears to be associated with prolonged exposure to vibration, whereas discomfort at the lower-back appears to be associated with prolonged static posture.

The following remarks summarize the other main subjective results and present possible mechanisms that could explain the SDTD due to prolonged exposure to whole-body vibration.

The subjective study showed the following other main results:

- The vibration amplitude required to keep a constant discomfort decreases with increasing duration of vibration exposure (except for 1-Hz lateral and 0.5-Hz fore-and-aft sinusoidal, 4-Hz and 8-Hz vertical narrowband random stimuli),
- SDTD depends on the vibration characteristic (especially with frequency and direction of excitation),
- SDTD depends on body support/restraint,

The results presented in Section 3.7 showed that SDTD depends on various parameters. Sections 3.8.2, 3.8.3, 3.8.4 and 3.8.5 discussed the relationships between the vibration characteristics and locations of discomfort to determine possible causes of the subjective discomfort time-dependencies.

From the results obtained, it seems that neck muscle activity and SDTD depend on two main parameters, the body support/restraint and the frequency of excitation.

Neck muscle activity appears to depend on the head motions and therefore on the vibration transmitted from the seat to the head. The ability of the trunk to attenuate the vibration transmitted to the head could be critical for neck muscle activity and SDTD. The backrest provides different trunk supports that depend on the direction of excitation. In the fore-and-aft direction, the backrest restricts the trunk motions and its ability to attenuate fore-and-aft vibration transmitted to the head. For lateral and vertical excitation the backrest provides less trunk support/restraint. It is therefore expected that there will be greater head motions, more neck muscle activity and therefore greater SDTD with fore-and-aft excitation than lateral or vertical excitation. However it is not recommended to eliminate all trunk support. Without a backrest, the spine is not supported and the back muscles will have to support the static load of the body and the load produced by the vibration excitation. This posture could generate greater SDTD from the static loading.

The second main parameter affecting SDTD is the frequency of excitation. The subjective results showed that 1-Hz stimuli generated less SDTD than higher frequency stimuli. This suggests that the head response to vibration is different between 1-Hz stimuli and higher frequency stimuli. It appears that a different type or quantity of muscle activity may be required to control head motions at 1Hz and at higher frequencies.

Further studies of the type and quantity of muscle activity used at 1 Hz and at higher frequencies and of the corresponding head motions should improve understanding of the mechanisms responsible for SDTD.

The findings developed in this chapter have been formulated as hypotheses for the studies presented in Chapter 5 and Chapter 6. Chapter 5 investigates the effects of the frequency of fore-and-aft vibration on the type and quantity of neck muscle activity produced during exposure to vibration. Chapter 6 presents the seat-to-head transmissibility and its relationship with neck muscle activity and SDTD.

3.9 CONCLUSION

A new method was designed to measure and compare the subjective discomfort time-dependencies (SDTD) produced by various types of vibratory excitation. This method involved exposing subjects to stimuli that generated a similar level of discomfort during the first 10 seconds of exposure. This was achieved either by using magnitude estimation tests or the weighted r.m.s. acceleration calculated using the ISO 2631 (1997). Once the equivalent discomfort magnitudes had been obtained, subjects were exposed to only one stimulus per session. During the session, subjects used the discomfort experienced during the first 10 seconds of exposure as a reference, and kept constant this level of discomfort by adjusting with a knob the vibration magnitude.

With this method, discomfort time dependencies for sinusoidal (1 Hz and 4 Hz), narrow-band random (1 Hz, 4 Hz, 8 Hz, and 16 Hz) and shock stimuli have been measured. Two other conditions were tested to investigate the effects of low frequency excitation (a fore-and-aft sinusoid at 0.5 Hz) vibration and body restraint (use of a 4-point harness during prolonged exposure to a 1-Hz lateral sinusoid) on the discomfort time-dependencies.

The main results were:

- discomfort increases with increasing duration of vibration ,
- prolonged exposure to vibration generates discomfort at the neck,
- SDTD tends to be greater with fore-and-aft excitation than with lateral and vertical excitation,
- trunk restrain in the direction of excitation produces greater SDTD,
- the waveform of the vibration has almost no effect on the SDTD,
- the vibration frequency has a critical effect on SDTD, with 1-Hz stimuli producing less SDTD than higher frequency stimuli.

From the interpretation of these results, it was hypothesised that:

- the evolution of discomfort with exposure duration may be caused by the neck muscles used to control head motions,
- trunk support/restraint may reduce the ability of the body to attenuate vibration transmitted to the head and therefore produce greater SDTD,
- vibration at different frequencies may produce different types of head responses and therefore different types and quantity of muscle activity and SDTD.

SDTD may be caused by vibration transmitted to the head and the neck muscle activity produced to control head motions. These hypotheses are tested in Chapters 5 and 6. The goal of the following studies conducted in the thesis was to determine which type of muscle activity generates greater SDTD and what the characteristics of the corresponding head motions are. If the type of head motion causing SDTS is identified, a biodynamical model could help predict the evolution of discomfort with exposure duration.

4 SUPPORTING INFORMATION CONCERNING THE METHOD

4.1 INTRODUCTION

Previous methods used to evaluate the effects of whole-body vibration exposure duration on discomfort have been described in Chapter 2. It was concluded that these methods seemed to be not adapted to measure and compare the subjective discomfort time-dependency due to various stimuli of prolonged duration. The method developed in Chapter 3 allows for assessing the evolution of discomfort depending on the duration of vibration exposure. This method can also compare the subjective discomfort time-dependencies for different stimuli. Therefore the choice of this method has theoretical justifications.

Results obtained with this method showed that the discomfort time-dependency depends on the frequency of excitation. This result is critical because it indicates that standards such as ISO 2631 (1997) and BS 6841 (1987) (see Chapter 2, Figure 2.10 and Figure 2.11) should include effects of frequency in their time-dependencies.

In this Chapter 4, two more tests were performed to investigate aspects of the test procedures that might affect the theoretical robustness of the method. (The experiments conducted in the thesis are not presented in a chronological order. The study presented here was performed after the first fore-and-aft subjective studies have been conducted.)

4.2 OBJECTIVES

The objective of this study is to provide supporting information concerning the behavior of the psychophysical method used in Chapter 3.

The behavior of the method was investigated in two experiments:

- The first experiment was conducted to investigate the repeatability of the method. Two subjects performed six times one identical experimental condition. Their intra-subject variability indicates the repeatability of the method.
- The second experiment consisted of using an alternative method, which was used by Griffin and Whitham (1976). Their method is described in Section 4.4. The results obtained with the two experimental methods were then compared.

4.3 METHODOLOGY OF THE STUDY OF REPEATABILITY

4.3.1 Subjects

Two male subjects aged 26 and 27 years, participated in the study. Subjects completed a consent form before participating in the experiment. 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.

4.3.2 Apparatus

4.3.2.1 Subject environment

Subjects were seated on the same conventional car seat used during the previous subjective studies (see Chapter 3), with their feet supported on an adjustable footrest. The headrest was removed from the seat. The seat and footrest were fixed on a vibrator platform able to vibrate the seat in the fore-and-aft direction.

Subjects were sitting in a comfortable upright posture (with their back in contact with the backrest). Subjects were blindfolded and used headphones producing 75 dB(A) white noise to avoid visual or acoustic clues that could affect their judgment. For safety, subjects wore a loose lap belt

4.3.2.2 Generate and acquire the vibration

Identical procedures as those used in Chapter 3 to generate and acquire vibration were employed. Stimuli were created by MATLAB software (version R6a) and *HVLab* software (version 3.81). Motion signals were generated and acquired using *HVLab* software (version 3.81). One computer was used to generate the stimuli and another one to acquire the motion on the platform. Stimuli were produced by a digital-to-analogue converter and reproduced on a horizontal hydraulic vibrator capable of displacements of 1 metre (peak-to-peak). An accelerometer (Entran EGCS-do-10/V10/LM4) mounted on the vibrator platform was used to acquire the acceleration. Both the input signal and the resulting acceleration were low pass filtered at 40 Hz with analogical elliptic filters.

4.3.3 Experimental design

Each subject performed six times an identical session (one session per day). Each session was conducted for both subjects around the same time of the day (between 9 am and 12 am).

The stimulus used for the experiment was a 4-Hz fore-and-aft sinusoidal vibration at 0.25 $m.s^{-2}$ r.m.s. for a duration of 30 minutes.

As described in Chapter 3, subjects were exposed continuously to the stimulus, which was modulated in amplitude. During the first 10 seconds of exposure, subjects had to assess their discomfort and keep continuously the level of global discomfort constant by adjusting the magnitude of the stimulus using a knob (potentiometer). The intra-subjects variability obtained during the six sessions should reveal the repeatability of the method.

4.3.4 Procedure for data analysis

Results were analyzed as described in Chapter 3 in order to obtain normalized r.m.s. acceleration.

The evolution of the acceleration with the exposure duration represents the measured discomfort time-dependencies. For both subjects, the median, the 25th and 75th percentiles were calculated from the discomfort time-dependencies measured during the six identical sessions.

4.4 METHODOLOGY OF THE COMPARATIVE STUDY (GRIFFIN AND WHITHAM 1976)

4.4.1 Subjects

Twelve male subjects, aged between 23 and 28 years, participated in the study. All subjects completed a consent form before participating in the experiment. 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.

4.4.2 Apparatus

4.4.2.1 Subject environment

The subject environment was as described in Section 4.3.2.1. The environment is identical as the one used for the subjective trials conducted with the 4 Hz and 1 Hz sinusoidal fore-and-aft stimuli.

4.4.2.2 Generate and acquire the vibration

Stimuli were created by MATLAB software (version R6a) and *HVLab* (version 3.81) software. Motion signals were generated and acquired using *HVLab* software (version 3.81). One computer was used to generate the reference signal and acquire the motion on the platform. A second computer was used to generate the test signals. Only the test signal was modulated in amplitude and could be adjusted by the subject. Both signals (reference and test) were added before being amplified and reproduced on a horizontal hydraulic vibrator capable of displacements of 1 metre (peak-to-peak). An accelerometer (Entran EGCS-do-10/V10/LM4) mounted on the vibrator platform was used to acquire the acceleration. Both the input signal and the acceleration were low pass filtered at 40 Hz with analogical elliptic filters.

4.4.3 Experimental design

4.4.3.1 Task performed by the subjects

Subjects participated in two 36-minute vibration sessions. Both sessions consisted of 10-second periods of continuously alternating 4-Hz and 1-Hz fore-and-aft sinusoidal vibration. In one session the 4-Hz motion was set to be the reference motion while the 1-Hz motion was set to be the test motion. In the other session, the 1-Hz motion was the reference and the 4-Hz motion was the test. The test motion was modulated in magnitude.

The subjects were required to adjust the magnitude of the test motion to compensate for periodic changes in its magnitude made by the amplitude modulation and to maintain it at a level which produced similar discomfort to that caused by the reference motion.

4.4.3.2 Stimuli

The stimulus was composed of continuous pairs of reference and test motions. The magnitude of the reference was constant during the session, whereas the magnitude of the test was modulated. Pilot studies have shown that 3 times 10 seconds was a sufficient duration for the subjects to adjust the test magnitude to the level of discomfort identical to the one produced by the preceding reference motion. The amplitude modulation of the test motion changed after the presentation of three pairs of Reference-Test motions. Figure 4.1 shows the construction of the stimulus. A first signal was composed of 10 seconds of reference signal every 8 seconds. The second signal was composed similarly with 10 seconds of test signal every 8 seconds. This was done so the two signals could be added and generate a continuous stimulus.

For this experiment, four stimuli were produced:

- Stimulus 1, with 4-Hz being the reference and 1-Hz the test motion with a magnitude modulation A
- Stimulus 2, with 1-Hz being the reference and 4-Hz the test motion with a magnitude modulation A
- Stimulus 1, with 4-Hz being the reference and 1-Hz the test motion with a magnitude modulation B

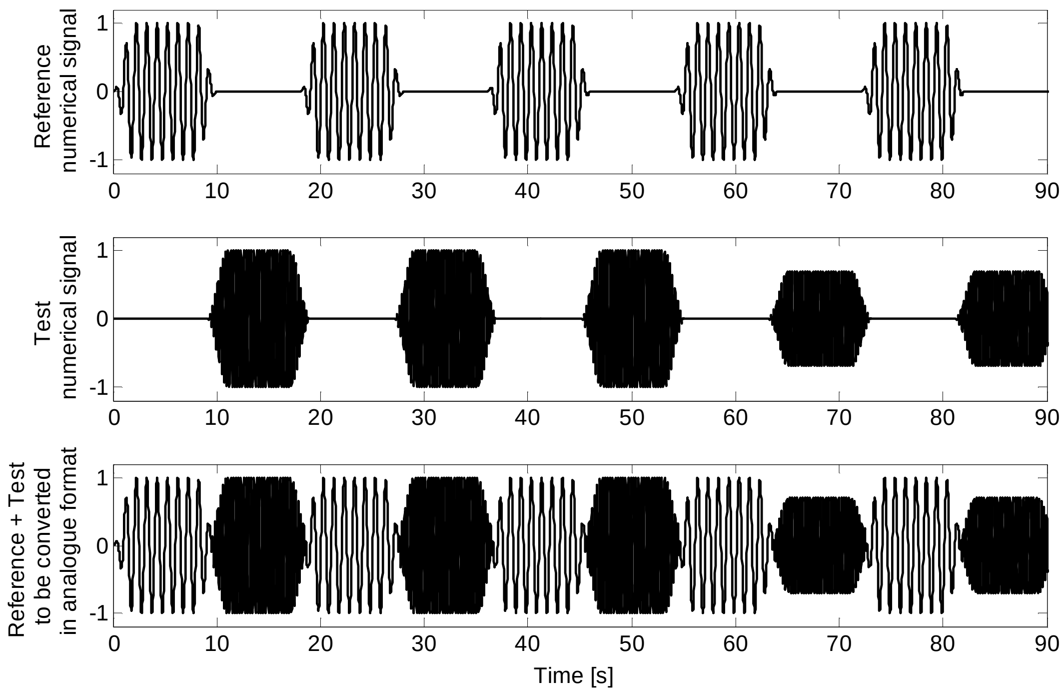


Figure 4.1 Reference and test signal are generated by two separate PC. Signals are added before being amplified and reproduced on the simulator. Subjects can adjust only the magnitude of the test signal. In this example, 1 Hz was the reference and 4 Hz was the test stimulus.

- Stimulus 2, with 1-Hz being the reference and 4-Hz the test motion with a magnitude modulation B.

The magnitude modulation A and B were designed so when modulation A shows an increase in magnitude, modulation B shows a decrease in magnitude of the same amount. Half of the subjects were exposed to stimuli with modulation A, the other half was exposed to stimuli with modulation B. This allows cancellation of the effects of the modulation on the subjective responses. Magnitudes of the test motion were modulated by steps of ±0.05 $m.s^{-2}$ r.m.s.

Stimuli were 1-Hz and 4-Hz sinusoidal fore-and-aft motions at 0.25 $m.s^{-2}$ r.m.s. According to results showed in Chapter 3 (Section 3.7.1), these two stimuli produce similar level of discomfort for short exposure duration.

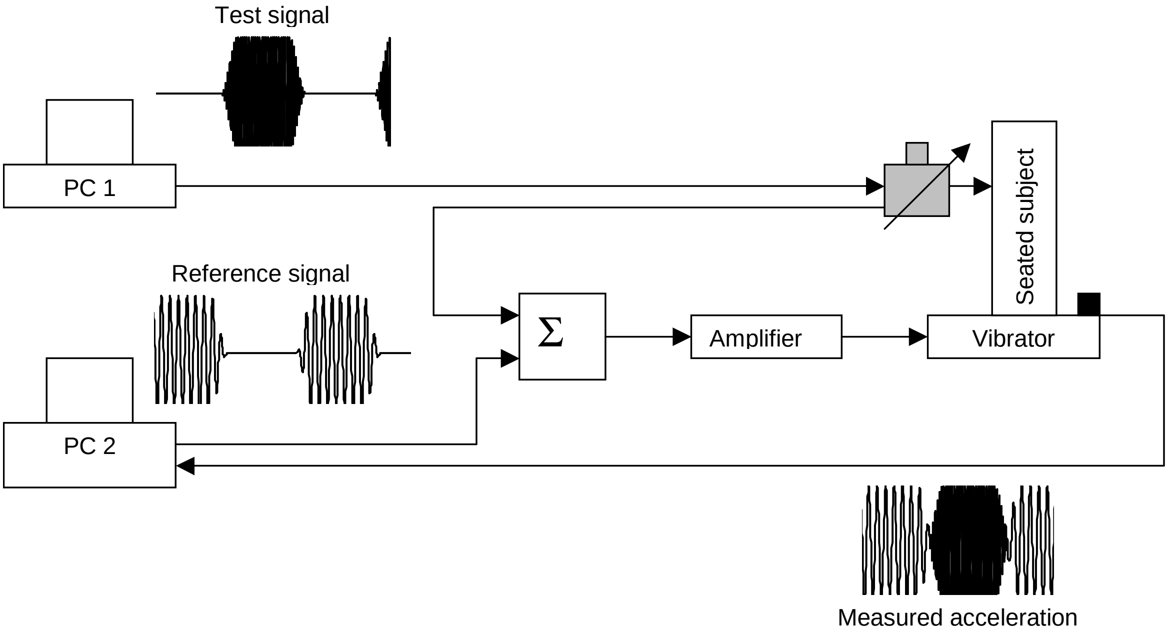


Figure 4.2 Experimental set up used to conduct the comparative study

4.4.3.3 Experimental set up

During the sessions, subjects were exposed to only one continuous stimulus that contained both the reference motion and the test motion. Subjects were required to adjust the magnitude of the test motion but the magnitude of the reference motion was not affected. Figure 4.2 shows how subjects could adjust the magnitude of the test motion without affecting the reference magnitude. It required two computers: one sending the reference signal and one the test signal. The test signal went through a potentiometer used by subjects to adjust the magnitude of the test motion. Then both signals were added together before being amplified and reproduced on the vibrator.

4.4.4 Procedure for data analysis

Each acceleration file was cut into segments to separate the reference motions from the test motions. The root-mean-square of the acceleration was calculated over a period of 6 seconds taken at the middle of each segment. The r.m.s. acceleration data points taken for analysis correspond to the r.m.s. acceleration of the last pair of reference-test stimuli before the magnitude of the test motion was altered by the modulation. Median data were calculated over the 12 subjects to illustrate the effect of vibration frequency on the comfort time-dependencies.

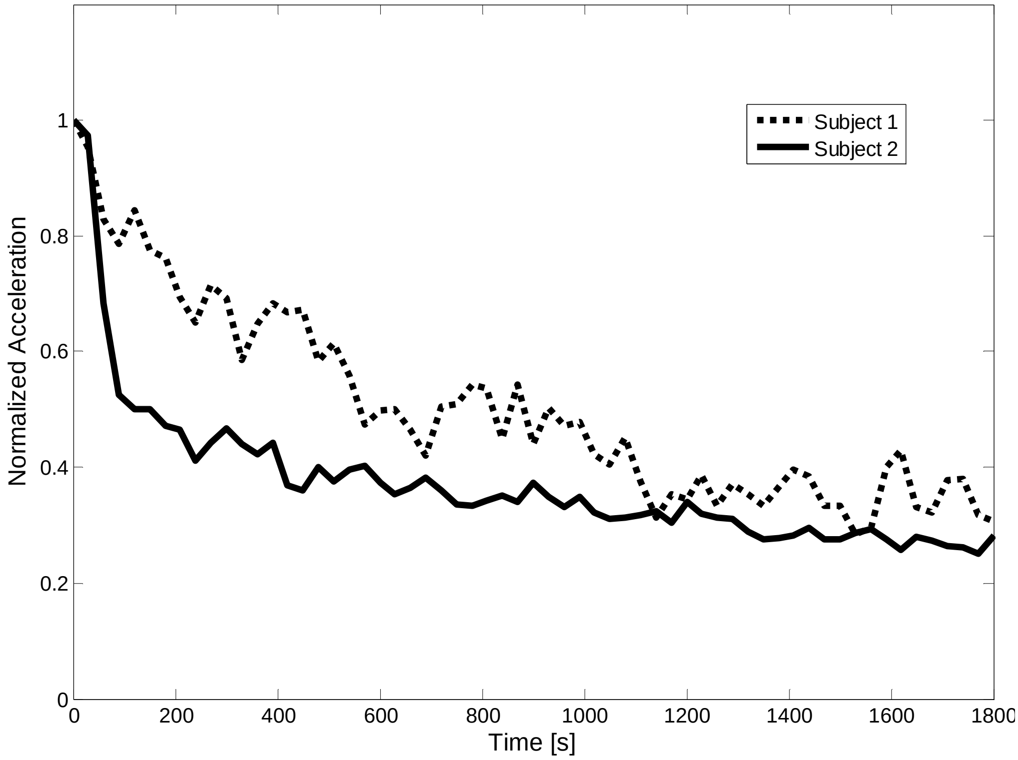


Figure 4.3 Median normalized r.m.s. acceleration calculated for the six sessions per subject.

4.5 RESULTS

4.5.1 Study of Repeatability

Figure 4.3 shows the median normalized r.m.s. acceleration calculated from the six sessions performed by both subjects.

Statistical analysis was performed, using the r.m.s. (integration time of 10 seconds) normalized acceleration calculated every 10 minutes during each of the six sessions. Figure 4.4 shows these data as used for the statistical analysis. The Friedman test was

Table 4.1 Results of the statistical analysis performed for the repeatability study (*p* values of the Wilcoxon test).

	Wilcoxon	**10th minute**	**20th minute**	**30th minute**
Subject 1	**0 minute**	0.017	0.022	0.026
Subject 2	**0 minute**	0.006	0.006	0.015

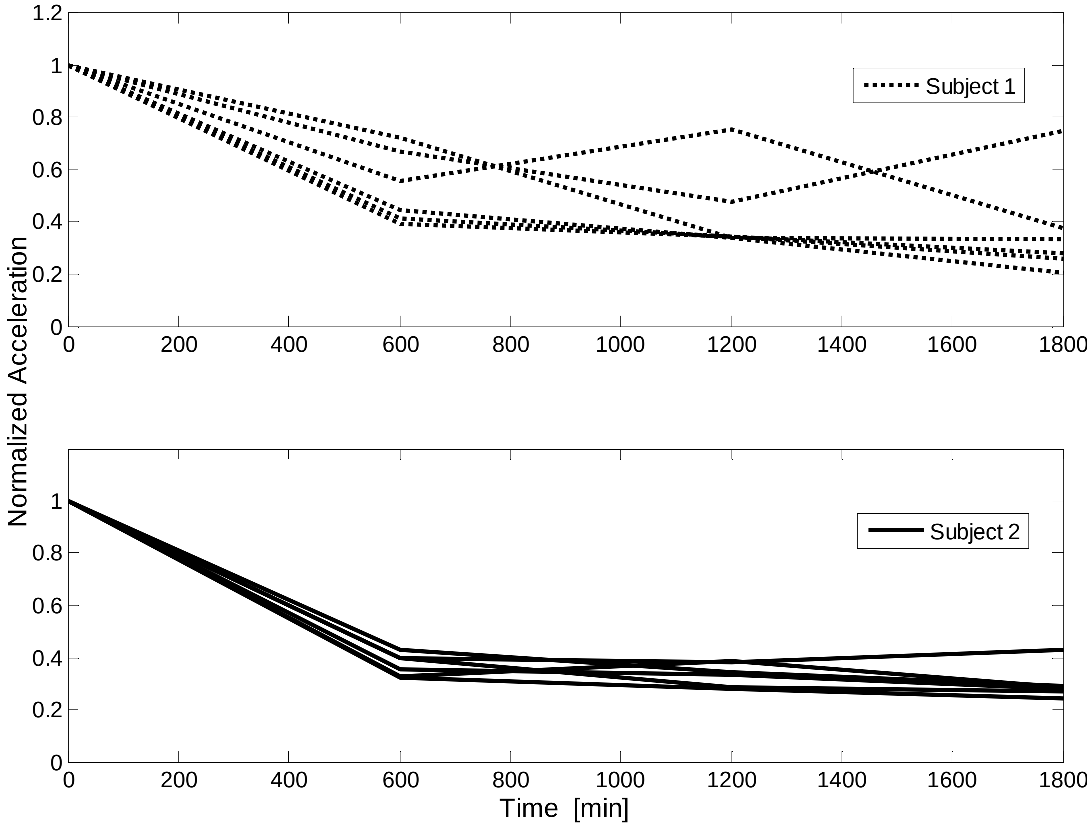


Figure 4.4 Median normalized r.m.s. acceleration calculated in each session for both subjects.

conducted to determine, for each subject, any significant difference ($p<0.05$) between the normalised acceleration measured at the beginning of exposure and the normalised acceleration taken every ten minutes. If significance is found, the Wilcoxon matched-pairs signed rank test for two related samples was used (see Table 4.1).

Results showed that for each subject, the acceleration measured after 10, 20 and 30 minutes of exposure was significantly different from the starting acceleration. As expected, the acceleration reduced with increasing duration, indicating that the discomfort caused by a fixed level of vibration increased for both subjects with increasing exposure duration.

Figure 4.5 shows the 25th and 75th percentiles, representing the spread in the data, and indicates that the method is probably repeatable.

4.5.2 Comparative study

Figure 4.6 shows median results of the comparative study. The upper graph shows the results of the session where 1-Hz was the reference motion and 4-Hz the test motion. The

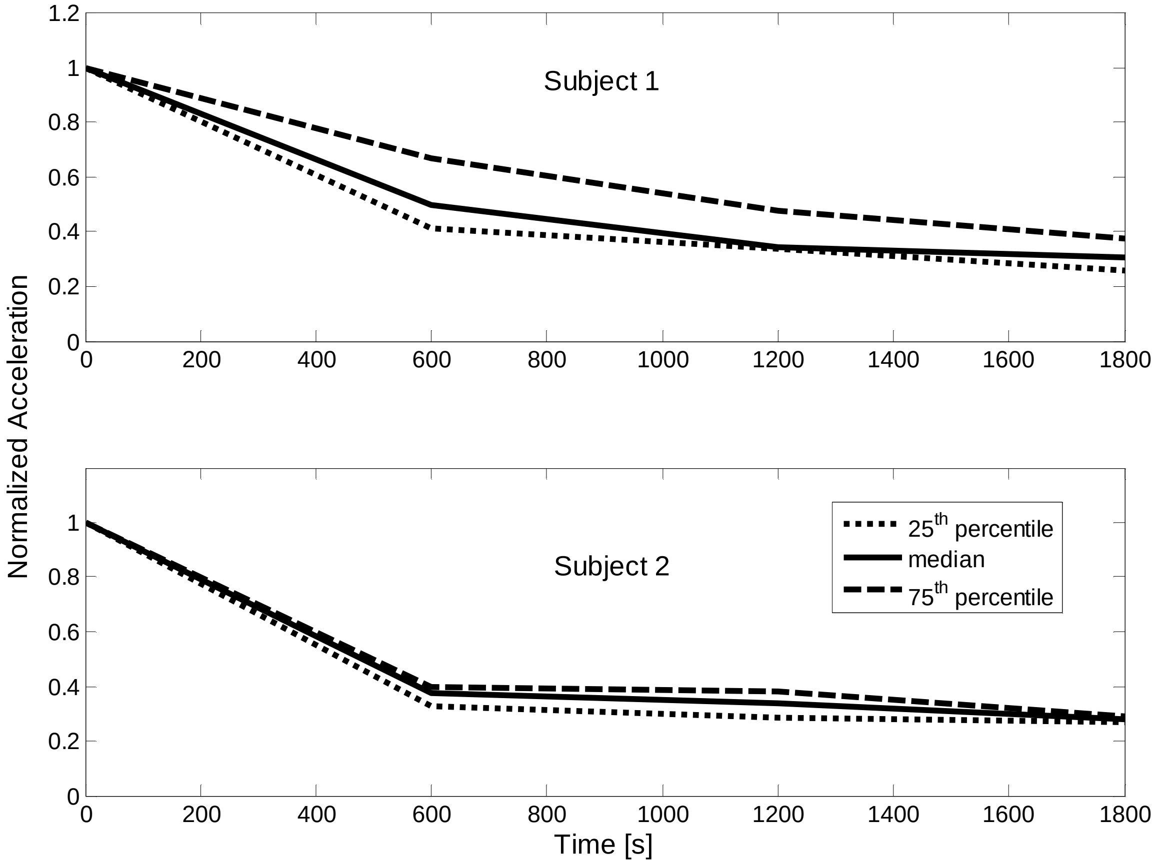


Figure 4.5 Spread of the data per subject: median, 25th and 75th percentile.

lower graph shows the results where 4-Hz was the reference and 1-Hz the test motion. The graphs show that subjects reduced the magnitude of the 4-Hz motion when 1-Hz was the reference stimulus, and increased the magnitude of the 1-Hz motion when 4-Hz was the reference stimulus. This means that, after a short exposure duration, subjects found the 4-Hz sinusoidal motion more uncomfortable than the 1-Hz motion.

The Friedman test was conducted to determine for both sessions, any significant difference (i.e., $p<0.05$) in the level of acceleration of the reference motion and the level of acceleration of the test motion. For the analysis, a pair of data points (reference and test acceleration) was taken after the 41st, 95th, 583rd, 1232nd and 2044th second of exposure. When statistical significance was found, the Wilcoxon matched-pairs signed rank test for two related samples was used (see Table 4.2).

In each condition, whether the 4-Hz motion was the reference or the test stimulus, the 4-Hz motions produced a significantly greater discomfort than 1-Hz motion after the first 95 seconds of exposure.

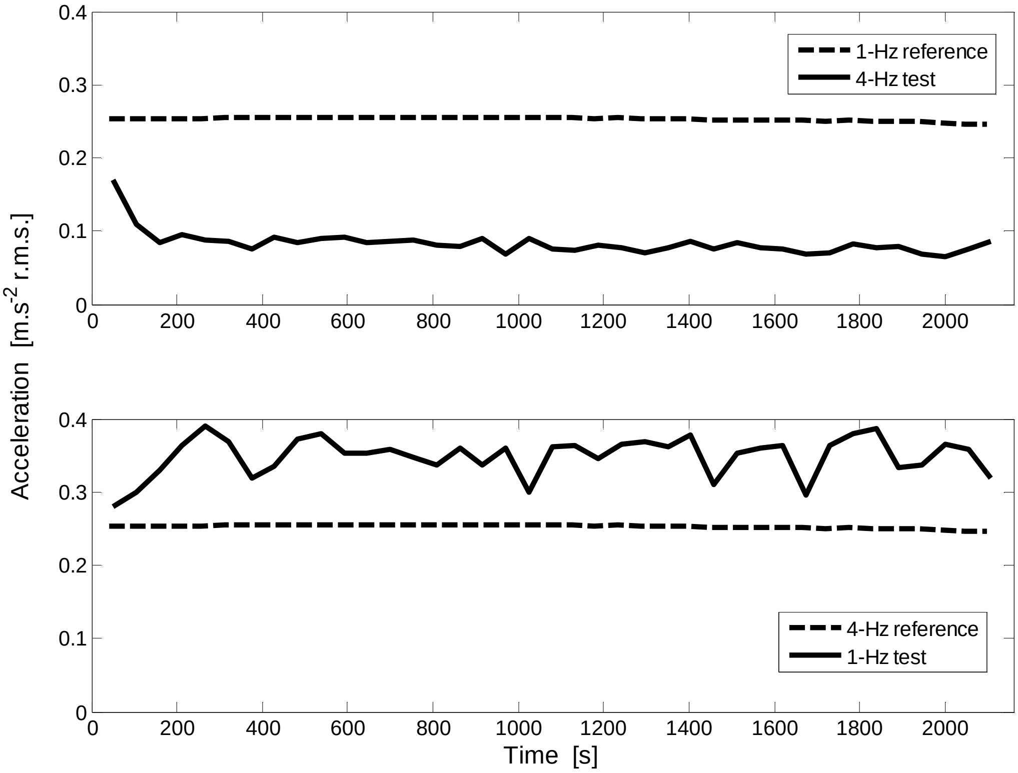


Figure 4.6 Median r.m.s. acceleration from 12 subjects. The top graph shows the median data where subjects adjusted the 4-Hz test stimulus so as to feel the same discomfort than the 1-Hz reference stimulus. The second graph shows the median data where subjects adjusted the 1-Hz test stimulus so as to feel the same discomfort than the 4-Hz reference stimulus.

The data showed that it took only 120 seconds of exposure for the subjects to decrease the 4-Hz sinusoidal motion from 0.25 to 0.1 $m.s^{-2}$ r.m.s. It took the same amount of time for subjects to increase the 1-Hz sinusoidal motion level from 0.25 to 0.35 $m.s^{-2}$ r.m.s. The relative comfort produced by 1-Hz and 4-Hz excitation changes most during the first two

Table 4.2 Results of the statistical analysis performed for the comparative study (*p* values of the Wilcoxon test

Wilcoxon	41st second	95th second	583th second	1232th second	2044th second
1 Hz Test Vs 4 Hz Ref	0.102	0.019	0.026	0.032	0.010
1 Hz Ref Vs 4 Hz test	0.192	0.037	0.015	0.019	0.011

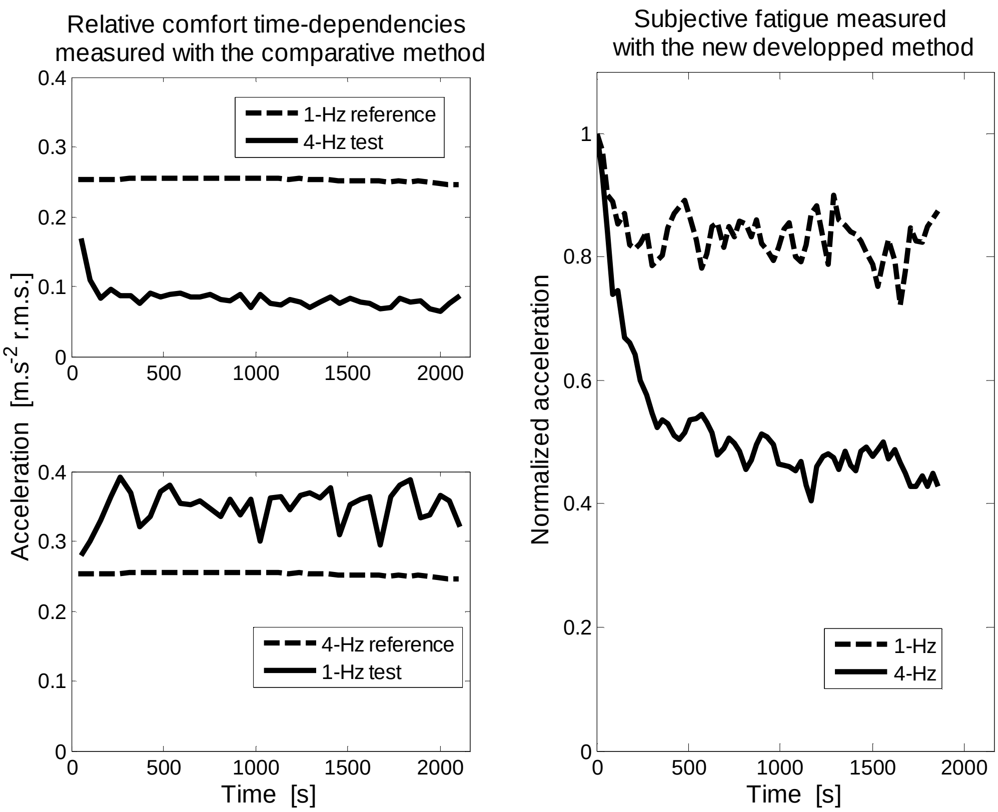


Figure 4.7 On the left**:** median r.m.s. acceleration from 12 subjects. The top graph shows the median data where subjects adjusted the 4-Hz test stimulus so as to feel the same discomfort than the 1-Hz reference stimulus. The second graph shows the median data where subjects adjusted the 1-Hz test stimulus so as to feel the same discomfort than the 4-Hz reference stimulus. On the right: normalized median acceleration obtained with 12 subjects representing the comfort time-dependencies of 1-Hz and 4-Hz stimuli.

minutes of exposure. After 200 seconds of exposure, the relative discomfort produced by 1-Hz and 4-Hz excitation is less dependent on changes in duration.

Figure 4.6 also shows that the ratio between the reference and test magnitude is different depending on whether 4-Hz is the reference stimulus or the test stimulus (respectively, the top graph and the bottom graph in Figure 4.6).

Figure 4.7 compares the results obtained with the comparative method and the results obtained in Chapter 3 with fore-and-aft sinusoidal excitation at 1 Hz and 4 Hz. The subjective discomfort time-dependency (SDTD) curves present the normalized acceleration required to maintain an equivalent level of overall discomfort: if the normalized acceleration decreases with increasing duration, discomfort is assumed to increase with increasing exposure duration. Figure 4.7 shows that both methods suggest that discomfort increases with increasing exposure duration, with 4-Hz sinusoidal fore-and-aft excitation generating greater SDTD than 1-Hz excitation. However the methods seem to provide different discomfort time-dependencies.

4.6 DISCUSSION

4.6.1 Study of repeatability

The study of repeatability showed that each of the two subjects, who participated in the experiment, responded similarly each time they were exposed to the same stimulus. The results showed that for these two subjects the method established in chapter 3 is repeatable.

Although, there is no apparent reason that the method would not be repeatable for other subjects and other stimuli, the repeatability of the method may need to be further tested with more subjects and more stimuli. If the results confirm the results obtained in this study, then the repeatability of the method will be confirmed..

4.6.2 Comparative study

The results obtained with an alternative method (Griffin and Whitham, 1978) and with the method established and described in Chapter 3, show differences and similarities. Both methods showed that 4-Hz sinusoidal fore-and-aft excitation produces a greater subjective discomfort time-dependency (SDTD) than 1-Hz. However discomfort produced by the exposure to the 4-Hz stimulus seems to increase at a faster rate with the alternative method than with the new method. Also, after 120 s of exposure the alternative method showed little effect of the exposure duration on discomfort, whereas the new method showed that the acceleration amplitude required to keep constant the discomfort continued to decrease with duration (even if the rate is lower than during the first 10 minutes of exposure).

It could be discussed that the subjective discomfort time-dependencies obtained by the two methods are not directly comparable. The acceleration magnitude of the test stimulus obtained with the alternative method cannot be compared directly with the magnitude of the test stimulus acquired with the new method. With the alternative method, subjects are exposed to two stimuli, which alternate: the reference and the test stimulus. The effect of prolonged exposure to the reference stimulus may also affect the response of the subjects to the test stimulus. In Figure 4.6, the results of the alternative method showed that the ratio between the amplitude of the reference and the test magnitude is different depending on whether 4-Hz is the reference stimulus or the test stimulus. Probably the main reason explaining this difference is that the discomfort produced by the reference stimulus changes with exposure duration. If the reference stimulus, after prolonged exposure, produces more discomfort, the magnitude of the test stimulus acceleration needed to reach a similar level of discomfort will be less. Therefore the difference between the amplitude of the reference and test stimuli will be greater when the SDTD of the test stimuli is less than the SDTD of the reference stimulus. This result tends to confirm that, for prolonged vibration exposure, discomfort is greater for 4-Hz motion than 1-Hz motion.

Figure 4.8 compares the results obtained with both methods on the same graph. For this purpose, the 1-Hz SDTD curve was normalized with respect to the 4-Hz SDTD curve (SDTD curves obtained in Chapter 3) and compared to the 1-Hz test stimulus normalized to the 4-Hz reference stimulus obtained in the comparative study. The same process was performed for the 4-Hz stimuli. This ‘normalisation’ was done to reduce the effects of the prolonged exposure to the reference stimulus used in the alternative method. Figure 4.8 shows some similarities between the results obtained with the two methods. However it cannot be confirmed that the two methods gave identical subjective discomfort time-dependencies. It can only be concluded that the two methods showed that after prolonged exposure to vibration, 4-Hz fore-and-aft sinusoidal vibration generates more discomfort than 1-Hz fore-and-aft sinusoidal vibration.

4.7 CONCLUSION

This Chapter presented two studies conducted to justify the theoretical robustness of the psychophysical method established in Chapter 3.

The results of the repeatability study showed that for two subjects the method seems repeatable as the subjects produced similar results for the six identical sessions. The repeatability could be further tested by increasing the number of subjects and by using more stimuli.

An alternative (Griffin and Whitham, 1976) method was used and its results compared with the subjective results obtained in Chapter 3. Although the subjective discomfort time-dependencies obtained are not identical, both methods indicate that discomfort increases with increasing duration of vibration exposure and that the SDTD of 4-Hz vibration is greater than 1-Hz vibration. This is an encouraging result that improves the confidence in the accuracy of the method.

5 PHYSIOLOGICAL STUDIES

5.1 INTRODUCTION

Subjective experiments (Chapter 3) have shown that different frequencies of excitation produce different subjective discomfort time-dependencies (SDTD). They also showed that dynamic discomfort was mainly located at the neck. It was assumed that different excitations produced different motions of the head. Therefore the neck muscles may be the cause of the discomfort experienced by the subjects and explain the discomfort time-dependencies measured. It was hypothesised that neck muscle activity would provide a physical measure correlated with discomfort experienced during prolonged exposure to vibration.

For most stimuli, fore-and-aft excitation generated greater SDTD than lateral and vertical excitation. Neck muscle activity was therefore measured with fore-and-aft excitations where the effect of the vibration characteristics on the time-dependency was the greatest.

The next section of this chapter introduces the principles of electromyography, presents current recommendations for acquiring SEMG signal, and reviews the few EMG studies conducted during exposure to whole-body vibration. The chapter then presents the objectives and hypotheses of the study, describes the methodology used, and presents the results obtained.

5.2 MUSCLE ACTIVITY: BACKGROUND

This section is largely based on three textbooks providing information on the measurement of muscle activity: “The ABC of EMG” by Konrad, 2005; “Muscles alive” by Basmajian and De Luca, 1985; “Selected topics in surface electromyography for use in occupational settings” from US Department of Health and Human Services, Expert Perspectives DHHS NIOSH Publications #91-100, 1992.

5.2.1 Principles of EMG

5.2.1.1 Anatomy of the muscle

Muscles are tissues with the primarily function of providing the motion and stability of the body. There are three types of muscle: “skeletal muscle”, “cardiac muscle” (heart muscle) and “smooth muscle” (localized in the walls of arteries and bowel). In this thesis the muscle of interest is the skeletal muscle, which is responsible for moving extremities and external areas of the body. Skeletal muscle was so named because it is attached to the bones of the skeleton.

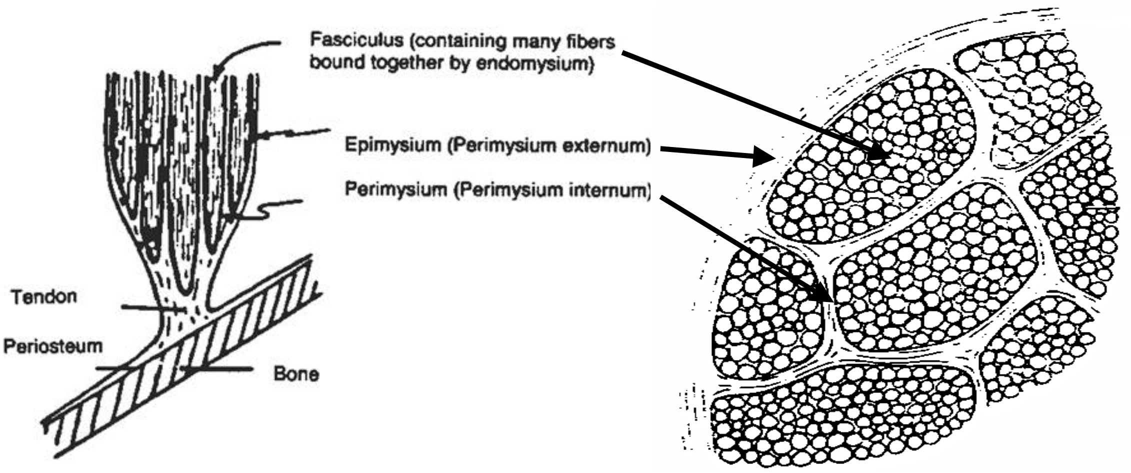


Figure 5.1 Anatomy of the muscle. A muscle is composed of group of fibres (from Lamb and Hobart, 1992)

The skeletal muscle is a contractile tissue composed of groups of fibres (see Figure 5.1). Each fibre is made up of smaller protein filaments called myofibrils. The myofibrils are made up of even smaller protein called the myofibril. The myofibril is also composed of a series of sacomeres arranged end to end (actin and myosin filaments) (see Figure 5.2). The contraction of the muscle is produced by an excitation of the fibre that generates the sliding of the actin over the myosin filament.

5.2.1.2 The action potential

Resting membrane potential

A muscle fibre is surrounded by the sarcolemma. The sarcolemma is a thin semipermeable membrane that has channels by which ions can move between the intracellular and the extra cellular fluid. The composition of the extracellular and the intracellular fluid are different. The intracellular fluid has a high concentration of potassium

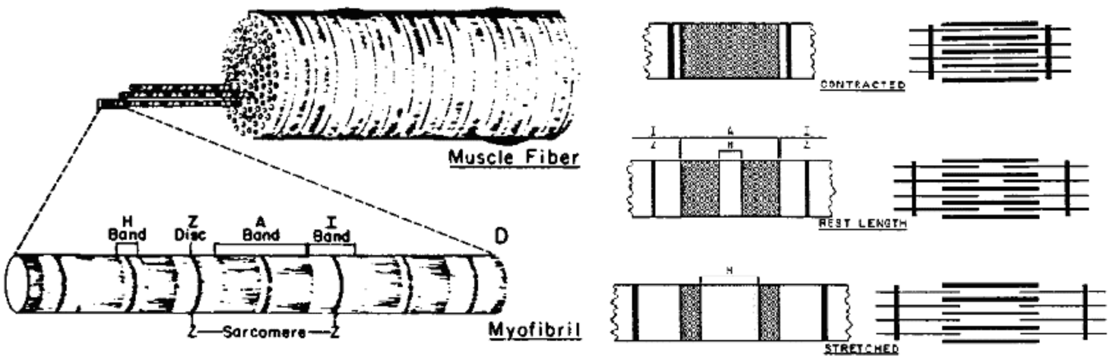


Figure 5.2 Composition of a muscle fibre (from Lamb and Hobart, 1992)

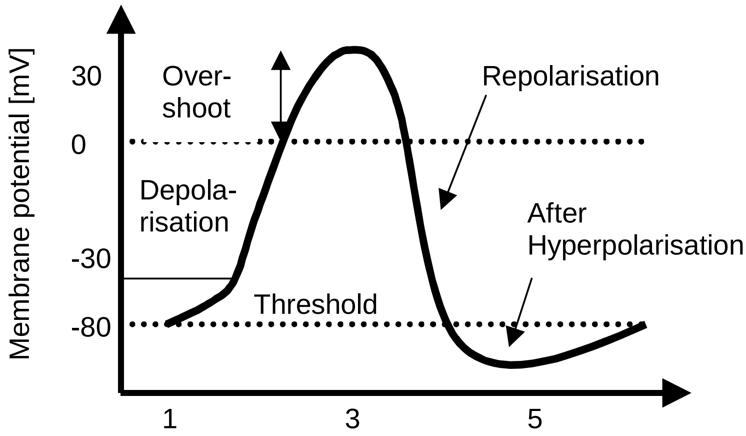


Figure 5.3 The action potential

(K^+) and an organic anion (A^-). Only the K^+ ions can pass though the membrane. The extracellular fluid has a high concentration of sodium (N+) and chloride (Cl^-) ions. The Cl^- are small enough to pass trough the membrane channels, but the slightly larger Na^+ ions have difficulties in penetrating the membrane. The potential of the membrane is generated by the movement though the channels of the K+ and Cl- ions. A sodium-potassium pump maintains this potential. This voltage difference is the resting membrane potential and measures about –80 mV inside the muscle fibre with respect to the outside. The polarized muscle fibre remains in equilibrium until excited by a stimulus

Muscle fibre action potential

Several events must occur before a fibre contracts. The starting point is the central nervous system that initiates a stimulus that is propagated to the spinal cord to the motor neuron. The motor neuron transmits the excitation through an axon. An axon has a number of dendrites. Each dendrite is connected to a fibre through the endplate. At the endplate a chemical reaction increases the permeability of the fibre membrane to the Na+. The rapid influx of Na+ into the muscle fibre generates a depolarization of the muscle fibre. When the depolarization becomes greater than a threshold, the fibre reverses polarity and reaches about +20 mV inside relative to the outside (see Figure 5.3). Near the peak of the reverse polarity the decreased influx of Na+ and increased efflux of K+ causes a rapid repolarization of the muscle fibre. When depolarization of the membrane under the motor neuron endplate occurs, a potential difference is established between the active region and the adjacent inactive regions of the muscle fibre. Ion current therefore flows between the active and inactive regions. This current flow decreases the membrane potential of the inactive region to a point where the membrane permeability to Na+ rapidly increases in the inactive region and an action potential is generated. In this manner, the action potential propagates away from the initial active region in both directions along the muscle fibre. The propagated action potential along the muscle fibre is called the muscle fibre action potential (see Figure 5.4).

5.2.1.3 Composition of the EMG signal

The depolarization and repolarisation cycle forms the EMG signal. The EMG signal can be observed from the potential difference between two electrodes.

Figure 5.5 shows the motor action potential for one fibre. Before the depolarized zoned (or active zone) arrived at the first electrode, the difference of potential between the electrodes is null. When the depolarized zone reaches the first electrode, the difference of the potential between the electrode increased (+20 mV - -80 mV = 100 mV). When the active zone is between the electrodes the difference of potential comes back to zero. When it reaches the second electrode the difference of potential decreases (-80 mV - +20 mV = -100 mV), before coming back to zero once the depolarized zone has passed the site of the second electrode. Depending on the conduction velocity and the distance between the two electrodes, the EMG signal from the action potential of one fibre can be assimilated as a sine wave (see schema 6 of the Figure 5.5).

However in practice, the electrodes pick up electrical signals from more than one muscle fibre. A motor neuron excites various fibres (see Figure 5.6), and during a contraction, more than one motor neuron can be excited. The EMG signal is the superposition of each action potential accessible by the electrode sites. There are two types of electrodes, the

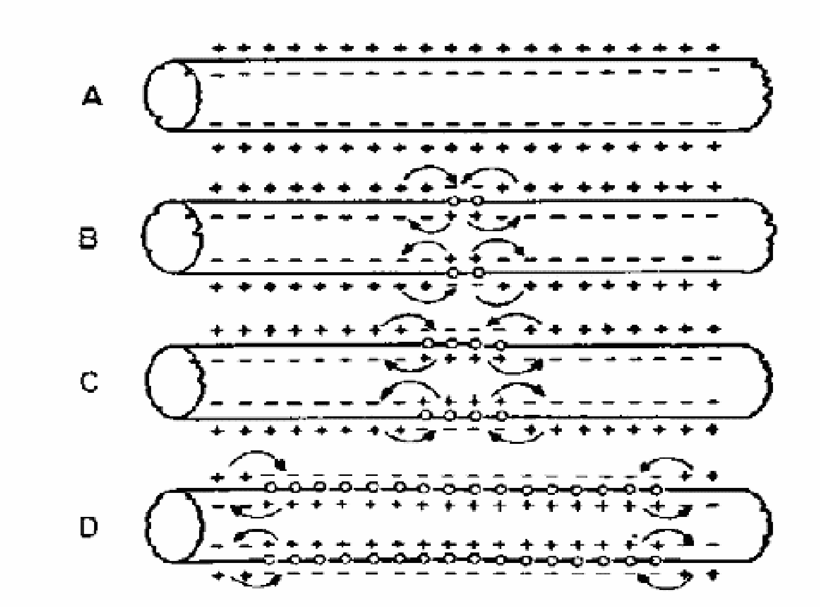


Figure 5.4 Propagation of action potential in both directions along a conductive fibre (Saunders, 1981)

needle electrodes and the surface electrodes. The needle electrodes can measure localized activity, from one muscle and few motor neurons. The surface electrodes are set up on the skin surface and measure the activity beneath it. They generally measure activity on a greater area that could include more than one muscle.

The contraction of the muscles depends on the number of motor neurons activated and the frequency at each they fire (frequency of excitation). The recruitment of motor neurons and their firing frequency are the two most important mechanisms influencing the magnitude and density of the observed EMG signals (see Figure 5.7). These are the main control strategies to adjust the contraction process and modulate the force output of the involved muscle.

An unfiltered and unprocessed signal detecting the superposed motor neuron action potentials (also called MUAPs: Motor Unit Action Potentials), is called a raw EMG signal. By its nature, raw EMG spikes are random in shape. Raw SEMG can range between +/- 5000 microvolts and typically the frequency contents ranges between 6 and 500 Hz, showing most frequency power between 20 and 150 Hz.

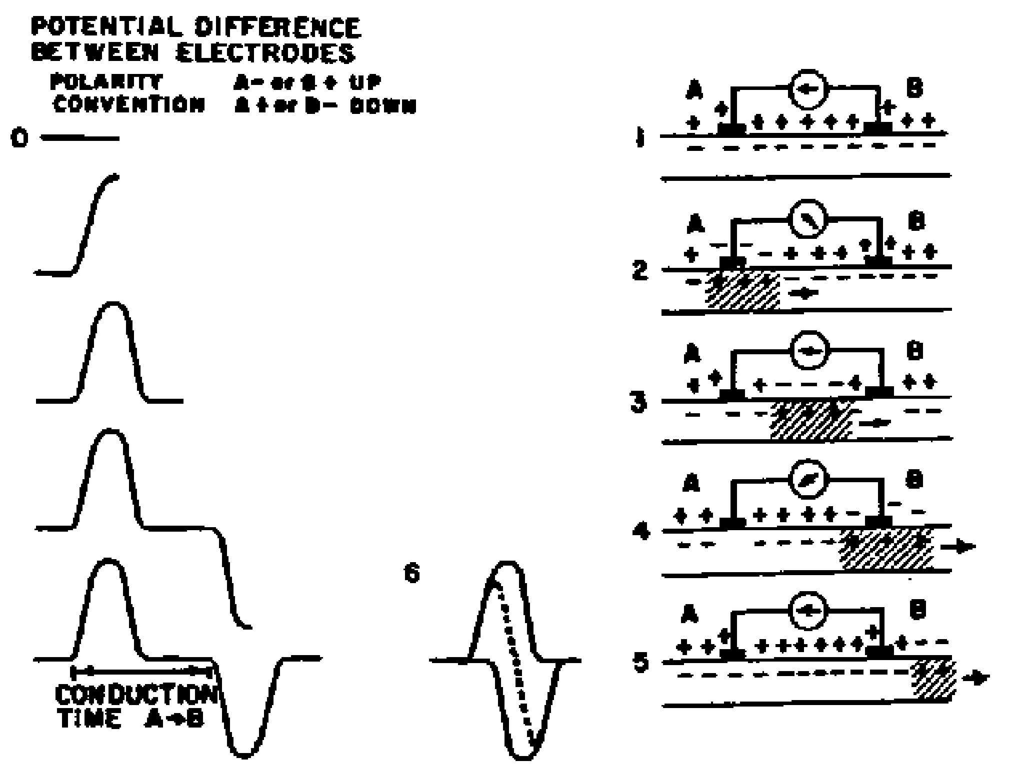


Figure 5.5 The measurement of action potential (from Wiley, 1972)

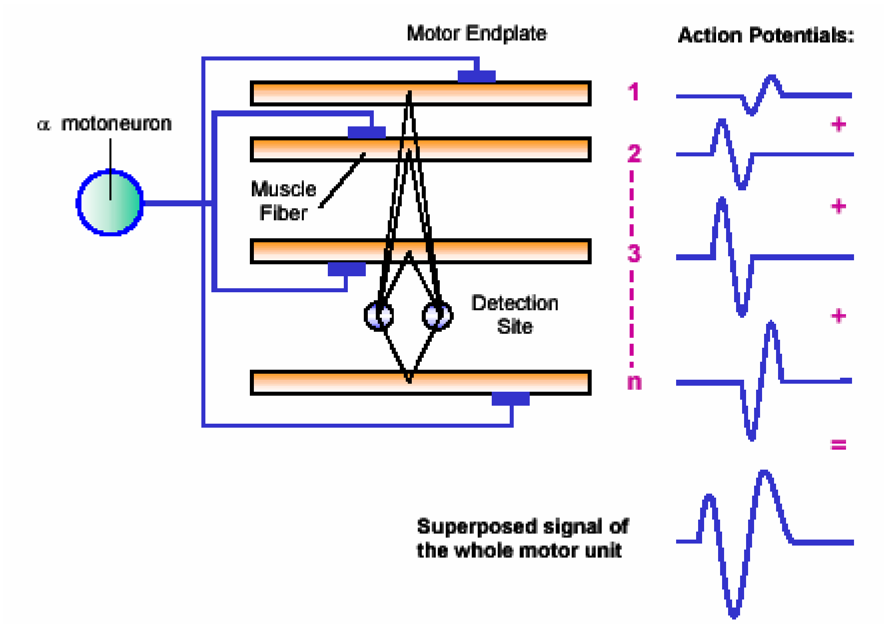


Figure 5.6 Generation of the motor unit potential generated from a motor neuron (from Konrad, 2005)

5.2.1.4 Factors influencing the measured EMG signals by surface electrodes

In this thesis, only surface EMG electrodes were used. From the muscle membrane up to the surface electrodes, the EMG signal can be influenced by several factors:

- Tissue characteristics

The electrical conductivity depends on the tissue type, thickness, physiological changes, and temperature. These conditions vary from subject to subject (even within subject), which prohibit direct comparison of the magnitude of EMG signals.

- Physiological cross talk

Cross talk can be produced by neighbouring muscles. The signal coming from the heart can also be acquired by the EMG electrodes especially when the measure is performed on the upper trunk or shoulder muscles.

- Electrode locations and displacement during the measure

Any change of distance between the original detection site and the electrode, due to dynamic movement studies, and movement of electrode cables will alter the EMG readings and may generate artefacts. The quality of contact between the electrode and the skin is also critical (see Section 5.2.2.2.1).

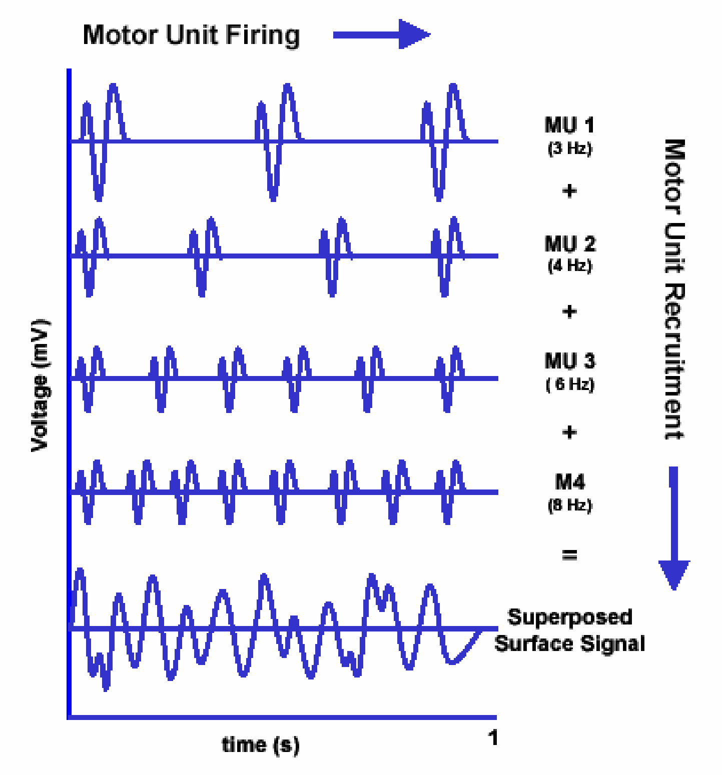


Figure 5.7 Recruitment and firing frequency of motor unit (from Konrad, 2005)

- External noise

Special care must be taken in noisy electrical environment. The grounding of the electrical equipment should be verified if the noise is too critical for the quality of the EMG measure.

- Equipment

The quality of the electrodes and the amplifier will affect significantly the measure of the EMG signal. The recommended equipment is described in Section 5.2.2.1.

5.2.2 EMG measurement recommendations

5.2.2.1 Recommendation for sEMG equipment

- *SENIAM* (Surface Electromyography for the Non-Invasive Assessment of Muscles) *recommendation for sensors (SENIAM, Hermens et al., 2000).*

SENIAM is a European concerted action in the biomedical health and research program of the European Union. The SENIAM project developed important guidelines for EMG measurements. SENIAM recommendations for sEMG equipment are related to:

- electrode shape and size

- inter-electrode distance
- electrode material
- sensor construction.

Electrode shape and size. There is no clear and objective recommendation for electrode shape. It is just recommended to indicate clearly the type, manufacturer, and shape of the electrode used. Concerning the size of the electrode, it is recommended that the size in the direction of the muscle fibres should not exceed 10 mm.

Inter-electrode distance. The inter-electrode distance is defined as the center-to-center distance between the conductive areas of the two bipolar electrodes. It is recommended to apply bipolar SEMG electrodes at the recommended sensor location (see Section 5.2.2.2.2) with an inter-electrode distance of 20 mm. For small muscle the inter-distance should not exceed one-quarter of the muscle fibre length.

Electrode material. The electrode material should realize a good electrode-skin contact (low impedance and stable behaviour). It is recommended to use pre-gelled Ag/AgCl electrodes.

Sensor construction. It is recommended to use a construction with fixed inter-electrode distance, built from light-weight material. The cable and the pre-amplifier (if applicable) should be fixed with tape or elastic band to reduce the movement artefacts.

- *Recommendation for electromyographic pre-amplifier*

There are two important properties to consider in a pre-amplifier:

- high common mode ratio
- very high input impedance

Common Mode ratio (CMRR). Bipolar electrodes are used with a differential amplifier, which suppresses signals common to both electrodes and amplifies the difference. The common mode rejection ratio provides an index on the extent to which common signal components are attenuated from the signal. It is therefore recommended to have the highest common mode ratio possible.

Input impedance. In order to measure a voltage accurately, the input resistance of the measurement should be considerably greater than the impedance at the skin. It is recommended to have an input impedance at least 100 times greater than the skin impedance. If the input impedance is not enough, the electrical signal will be attenuated and distorted.

Table 5.1 shows the recommendation for amplifiers according to the International Society of Electrophysiological Kinesiology (1980).

It is important to reduce the movement artefact and the noise coming from the cables. The distance between the signal source and the pre-amplifier should be reduced as much has possible. Modern equipment has the pre-amplifier set up just after the electrode measuring site.

DC components can be can be caused by factors involving skin impedance and the chemical reactions between the skin and the electrode gel. Any difference in the DC potential measured at each the electrode sensors will be amplified, which can lead to pre-amplifier instability or saturation. It is therefore important to have a DC signal suppression for each electrode.

5.2.2.2 Recommendation for skin preparation and sensors placement

Table 5.1 Recommended Minimum Specification for Surface EMG amplifier

Variables	**Recommended Minimal Specification**
Input Impedance	> 10^{10} Ω at DC or > 10^{8} Ω at 100 Hz
Amplifier Gain	200 - 100 000 ±10% in discrete increments
Gain nonlinearity	≤ ± 2,50%
Gain stability	Combined short term (1 day) and long term (1 year) gain variations <5% per year
Common mode rejection ratio	> 90 dB measured at 60 Hz with zero source resistance
Frequency response	1 - 3000 Hz measured at -3 dB points
Input bias current	< 50 nA
Isolation	≤ μA leakage current measured between patient leads and ground
Noise	< 5 μV RMS measured with a 100 kΩ source resistance

Skin preparation

A good skin preparation improves the quality of the skin-electrode contact. It allows a better SEMG-recordings (in terms of amplitude characteristics), fewer and smaller artefacts (electrical interference), less risk of imbalance between electrodes (smaller common mode disturbance signal) and less noise (better S/N ratio). The goal of the skin preparation is to obtain a skin impedance (between pairs of electrodes) lower than 50 kilohm. There are no general rules to process the skin preparation. "The SENIAM recommendations for skin preparation recommend shaving the patient if the skin surface at which the electrodes have to be placed is covered with hair. The next step is to clean the skin with alcohol and allow the alcohol to vaporize so that the skin will be dry before the electrodes will be placed" (www.SENIAM.org). If the cleaning of the skin with alcohol is not sufficient to lower the skin impedance below 50 kilohm, a light abrasion of the skin (with special abrasive and conductive cleaning paste or a very find sand paper) may be required. Whichever skin preparation method and electrode application technique is used, when done properly, the skin typically receives a light red colour. This indicates a good skin impedance condition.

Sensor placement

There are several steps to consider for the placement of the sensor (SENIAM, Hermens *et al.*, 2000):

- Selection of the SEMG sensor
- Preparation of the skin
- Positioning the patient in a starting posture
- Determination of the sensor location
- Placement and fixation of the sensor
- Testing of the connection

The first two steps of this list were described in Sections 5.2.2.1 and 5.2.2.2. After the sensor is selected and the skin prepared as recommended, the subject has to be placed in a posture which allows the determination of the proper location of the electrodes on the muscle. In this posture it is possible to determine the anatomical landmarks that help to determine the proper sensor location. The sensor location is defined as the position of the centre of the two bipolar electrodes on the muscle. Sensor should be placed at a location at which a high-quality and stable SEMG can be obtained. The stability of the SEMG signal can be strongly influenced by the presence of motor points and/or muscle tendons and the presence of other active muscles near the SEMG sensor. SENIAM has made recommendations for sensor placement for 27 muscles. The specific recommendations for each muscle have been based on two general starting points: "With respect to the longitudinal location of the sensor on the muscle, it is recommended to place the sensor halfway between the most distal motor endplate zone and the distal tendon. With respect to the transversal location of the sensor on the muscle, it is recommended to place the sensor at the surface away from the edge with other subdivisions or muscles so that the geometrical distance of the muscle to these subdivisions and other muscle is maximized." The two bipolar electrodes should be orientated parallel to the muscle fibres. A third electrode is used to increase the signal to noise ratio. This reference electrode is placed on electrically inactive tissue (such as bone). Testing of the connections is done by a specific motion for each muscle.

5.2.2.3 Measuring neck muscle activity

Observations of the motions of the head during exposure to fore-and-aft whole-body vibration suggest that the head moves in the sagittal plane. The muscle responsible of this type of motion was thought to be the semispinalis. The semispinalis are considered by many to play a vital role in the dynamic stabilization of the cervical spine (Nolan and Sherk, 1988).

Sommerich *et al.* (2000) reviews the use of surface electromyography to estimate neck muscle activity. This review addresses muscle selection and electrode placement. They confirmed that the semispinalis capitis is considered to be the primary head/neck extensor. To measure the muscle activity of the posterior muscles, which mainly includes the semispinalis, they recommend placing the electrodes according to the location used by Keshner *et al.* 1989), Mayoux Benhamou *et al.* (1995) or Queisser *et al.* (1994). These three studies used the following locations: "2 cm below occipital bone and 2 cm lateral from midline". This location should be considered as being a location-specific site, rather than muscle specific. This means that at this location, the activity of a group of muscles will be measured and not only the semispinalis capitis.

5.2.3 Measurement of EMG during exposure to vibration

5.2.3.1 Introduction

As shown in Section 5.2.1 changes in the myoelectric signal are based on the recruitment and firing rate of motor units within the muscle. The interpretation of the changes in recruitment and changes in firing rate can provide information concerning the muscle's level of force or its level of 'muscle fatigue'. These changes in the myoelectric signal can be observed in the time domain and quantified by the calculation of standard amplitude parameters (such as r.m.s.), or observed in the frequency domain by the calculation of a measure of the frequency content (such as the median frequency).

Measuring muscle activity produced by whole-body vibration exposure can provide other means to analyze the myoelectric signal relative to the properties of the excitation. The phase relationship between the muscle activity and the acceleration of the platform was used by some authors to investigate the effects of the frequency of excitation on the muscle response (see Section 5.2.3.4). The notion of phasic and tonic muscle activity was also introduced (see Section 5.2.3.5).

Investigations of the effects of low frequency (< 20 Hz) whole-body vibration exposure on muscle activity of seated subjects are rare in the literature. Generally the muscles studied are back muscles (mainly the erector spinae). The activity of the neck muscles in response to whole-body vibration has been reported in only a few studies.

This section classifies the muscle activity studies by the methods of analysis used to investigate the effects of whole-body vibration exposure on neck muscle activity (when available) and back muscles.

5.2.3.2 Effects of whole-body vibration on the amplitude of the EMG signals

The amplitude of the raw EMG signal indicates the state of activity of the investigated muscle. Inspection of the raw EMG signal is the first important step in the analysis.

After rectification of the raw signal, standard amplitude parameters such as the mean, peak and r.m.s. value can be calculated. This type of analysis can be used in studies investigating the effects of magnitude and frequency on neck and back muscles during exposure to whole-body vibration.

All studies reviewed found that the amplitude of the EMG signal acquired on the neck or back muscle increased with increasing vibration magnitude. Farah *et al*. (2006) found that passengers in cars produced greater neck muscle activity when exposed to high lateral excitation. Thuresson (2005) found that the neck muscle activity produced by vertical whole-body vibration increased with increasing vibration magnitude. Seidel (1988) found similar results with the back muscle of subjects exposed to vertical sinusoidal vibration.

Some studies also found effects of the frequency of excitation on the amplitude of the myolelectric signal. Thuresson (2005) found that the r.m.s. value of the EMG signal acquired at the neck during exposure to vertical sinusoidal whole-body vibration was greatest for vibration around 5 Hz. This is the frequency at which a resonance of the body is observed (e.g., Paddan and Griffin, 1988; Fairley and Griffin, 1989). Seidel *et al*. (1980)

investigated the effect of frequency and duration of vertical sinusoidal whole-body vibration on back muscle activity. They found that at 4 Hz, the EMG amplitude increased with increasing duration whereas at 8 Hz, no EMG time-dependency was observed. This result was consistent with the analysis of transmissibility and impedance conducted in the same study. The increase of the EMG amplitude corresponded to a decrease of the mean transmissibility.

The amplitude of the myoelectric signal was also used to investigate the effect of duration of whole-body vibration exposure. These studies are presented in the following section.

5.2.3.3 Effects of whole body vibration on 'localised muscle fatigue'

Some studies have investigated the effect of whole-body vibration on 'localised muscle fatigue' (Sheridan *et al.*, 1991; Park *et al.*, 2001; Falou *et al*., 2003). Localised muscle fatigue is a notion introduced by Chaffin (1973) to describe a condition in which discomfort due to prolonged static loading of the muscles is accompanied by a shift of power in the spectrum of the electromyogram to lower frequencies (Lindström *et al.*, 1977; Herberts *et al*., 1980). The frequency shift is also observed with an increase in the r.m.s. SEMG with increasing duration of muscle contraction (Cobb and Forbes, 1923; Lippold *et al.*, 1960). Long term driving has been reported to generate localised 'muscle fatigue' of both neck and back muscles (Sheridan *et al.,* 1991; Park *et al.,* 2001), but with no control condition it is not possible to conclude whether the localised 'muscle fatigue' was due to vibration or a prolonged static posture. A laboratory study investigating the effect of prolonged vertical whole-body vibration on various muscles (including neck muscles) did not find any difference in the shift to lower frequencies in the SEMG spectrum between conditions with vibration and a control condition (Falou *et al*., 2003). Current understanding does not allow a clear conclusion as to the effect of the frequency and duration of exposure to whole-body vibration on neck muscle activity.

Other studies investigating the effects of whole-body vibration on the 'muscle fatigue' of back muscles have shown divergent results. Some have found localized 'muscle fatigue' (e.g., Seidel *et al.,* 1980; Wilder *et al*., 1982; Pope *et al*., 1985; Seroussi *et al.,* 1985; Magnusson, 1991; Hansson, 1991), while others have not (e.g., Hosea *et al.,* 1986; Zimmermann *et al.,* 1993; De Oliviera and Nadal, 2004). The divergence may be explained by the different experimental protocols used. Studies finding an effect asked subjects to either wear a load carried by a harness attached to the chest and adopt an anterior lean posture (Magnusson, 1991; Hansson, 1991), or asked subjects to maintain an erect or forward bent posture with proprioceptive feedback (Seidel *et al*., 1980; Wilder *et al.,* 1982; Pope *et al*., 1985; Seroussi *et al*., 1985). This may mean that 'muscle fatigue' associated with whole-body vibration may only be observed with pre-loaded muscles.

5.2.3.4 Effects of whole-body vibration on the phase relationship between the excitation and the muscle response

Lippold *et al.* (1958) studied the effects of the vibration on the muscle electrical discharge produced by various muscles of the cat. They found that up to 15 Hz, the peak of electrical discharge appears at the moment of the greatest velocity. At higher frequencies, the motor electrical discharge was increasingly delayed. Surface and needle electrodes are used to record muscle activity in humans. Studies conducted with such electrodes have found that low frequency vertical vibration of the body produces synchronous changes in the myoelectrical activity of the back muscle (Guignard and Travers, 1959; Seidel *et al.,* 1986). These results indicate a potential effect of the frequency of vibration excitation on the phase relationship between the excitation and the muscle response.

The response of muscle to whole-body vibration can be further investigated by averaging the SEMG so as to observe the variation in muscle activity during complete cycles of sinusoidal oscillation (see Section 5.5.4 below). This method allows discriminating EMG signals and movement artefacts and obtaining measurements free of movement and ECG artefacts. Seidel (1988) and Robertson and Griffin (1989) used this method to investigate the phase relationship between the SEMG response of back muscles and the seat acceleration with sinusoidal vibration at different frequencies in the vertical direction. Seidel (1988) found that muscle activity was in phase with the vibration only at frequencies below 1 Hz, that between 2.5 Hz and 5 Hz the SEMG lagged the acceleration, and that the maximum amplitude of the muscle activity grew with increasing frequency of vibration (from 0.315 Hz to 5 Hz with the same acceleration at each frequency). Robertson and Griffin (1989) found that muscle activity led the platform acceleration at 4 Hz and lower frequencies. At higher frequencies, the EMG showed an increasing lag behind the acceleration. They also studied the phase relationship between the SEMG and fore-and-aft vibration and found similar trends in the muscle timing to those with vertical vibration, but with the maximum phase lead in the SEMG at 1 Hz (instead of 4 Hz for vertical vibration). Figure 5.8 shows the phase relationship obtained in the study of Robertson and Griffin (1989) between the averaged r.m.s. EMG and averaged fore-and-aft sinusoidal platform acceleration.

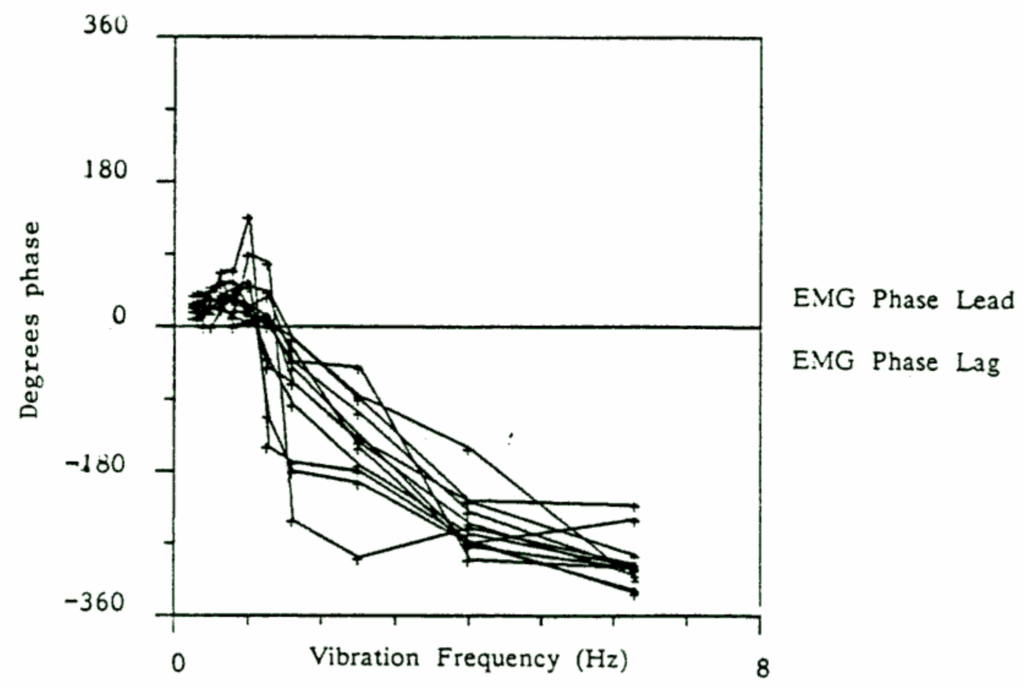


Figure 5.8 Phase relationship for 12 subjects between the averaged r.m.s. EMG and averaged fore-and-aft sinusoidal platform acceleration (from Robertson and Griffin, 1989).

5.2.3.5 Definition of the phasic and tonic muscle activity

Gail *et al*. (1966) was one of the first to introduce the notion of phasic and tonic properties of the muscles. He found that phasic reflexes such as the Achilles tendon reflex and the Hoffman reflex were reduced while a tonic contraction is produced by the vibrated muscle.

The calculation of the phasic and tonic activity (detailed in Section 5.5.4.4) is based on the averaging method used to study the phase relationship between the platform acceleration and the muscle response. This signal-averaging method enabled Seidel *et al.* (1985), Seidel (1988) and Robertson and Griffin (1989) to show the variation of the electromyographic activity of the erector spinae muscles of the back during complete cycles of sinusoidal oscillation. For example Robertson and Griffin (1989) found a significant increase in tonic activity after 90 minutes vibration exposure, whereas no change in the amplitude of the phasic component of the muscular activity was observed.

In this thesis, it will be assumed that the phasic activity is the muscle activity arising as a result of periodic vibration whereas the tonic activity is the muscle activity needed to respond to a static load.

5.2.3.6 Effects of posture and body support on muscular activity during exposure to vibration

Exposure to vibration can generate perturbations in maintaining a posture and induce illusions of muscle position. Vibration may degrade the information received from sensory systems by introducing a background noise which masks the signals normally used in maintaining postural equilibrium. Vibration can also produced signals to the sensory systems that are not properly interpreted (Griffin, 1990).

A basic ergonomic principle is that static muscular work should be reduced to a minimum. Anderson *et al.* (1974) conducted studies to investigate the influence of various postures and type of support on myoelectric activity and disc pressure. They found that muscle activity of the back was influenced by posture. The most critical support parameter affecting back muscle activity was the inclination of the backrest. The lumbar support had a minor influence on the myoelectric activity (but decreased the disc pressure).

In view of these results, one can expect that the combination of various postures and supports during exposure to whole-body vibration will have critical effects on the muscular activity. It has been said (in Section 5.2.3.4) that the different results observed in studies investigating the localized ‘muscle fatigue’ may be due to the different postures adopted. Studies investigating the effects of posture on the back muscle activity have shown that the posture of the body is a critical parameter to control when assessing muscle activity (Seroussi et al., 1985; Zimmerman et al., 1986).

5.2.3.7 Conclusion

The goal of the Section was to list, according to the parameters investigated, available methods for analyzing the myoelectric content of the muscle activity. The Section has also shown that the current understanding does not allow a clear conclusion as to the effect of the frequency of exposure to whole-body vibration on neck muscle activity

Analysis of the r.m.s. of the rectified normalized myoelectric muscle activity allows the level of muscle activity produced by various stimuli to be compared. However it does not describe the mechanisms responsible for muscle responses to the excitation. The r.m.s. information coupled with the spectral content of the EMG signal allows a better description of the muscle state of fatigue. However, as shown in Section 5.2.3.3., localized ‘muscle fatigue’ due to whole-body vibration is observable mainly when the muscle is pre-loaded either by an anterior posture or by an external load. Moreover this method of analysis seems inefficient for measuring the effect of the frequency of excitation on the muscle activity. The method most commonly used to investigate the effect of frequency is the calculation of the phase relationship between the platform acceleration and the myoelectric response of the muscle. Other tools such as the phasic and tonic activities, calculated with a similar averaging method used to provide the phase relationship seem to be the best adapted tools to improve the understanding of the muscle response to the vibration exposure. The phasic activity represents the periodic part of the muscle activity that responds to the excitation. The tonic activity represents the muscle activity need to respond to a static load. The proportion of phasic activity relative to tonic activity can represent how the excitation is perceived by the muscle. For example if the proportion of tonic activity is significantly greater than the phasic activity, the periodical excitation may not be 'perceived' as periodic by the muscle but more as a static load. This information can be used during the investigation of the effects of frequency of whole-body vibration on the muscle response.

Controlling the posture within subjects and within sessions was found to be fundamental when comparing muscle activity acquired during different sessions and with different subjects.

5.3 HYPOTHESIS OF THE EMG STUDY

Subjective studies (see Chapter 3) suggest that the evolution of discomfort with the duration of whole-body vibration depends on the frequency of excitation and its effects on the neck. It was hypothesised that the discomfort felt at the neck was due to neck muscle activity.

Because discomfort varies both with frequency and duration of exposure, it seems reasonable to expect that the content of the activity of the neck muscles varies with the frequency and duration of exposure in a way that could explain the subjective results.

From the review of the relevant literature, it was concluded (see Section 5.2.3.6) that the phasic and tonic activity could describe the different responses of the muscle due to the frequency of the whole-body vibration exposure. It was hypothesised that low frequencies of excitation generate more phasic activity than tonic activity and that this proportion is progressively reduced as the frequency increases.

5.4 OBJECTIVE OF THE EMG STUDY

The main objective of the study was to understand the variations in the response of the muscles relative to the frequency of excitation. Neck muscle activity is expected to provide a physical value giving evidence that the behaviour of the neck muscles is responsible of the subjective discomfort time-dependency (SDTD). Neck muscle activity could then be the basis of a predictive model of SDTD.

Neck muscle activity was measured on seated subjects during 10 minutes of whole-body vibration in the fore-and-aft direction at 0.5 Hz, 1.0 Hz, 2.0 Hz, 4.0 Hz, 8.0 Hz and 16.0 Hz. The fore-and-aft direction was chosen because it produced (for most stimuli) greater discomfort time-dependencies than vertical and lateral excitation. The duration was chosen to be 10 minutes because the sensitivity to vibration magnitude increased significantly during the first 10 minutes of exposure (see Chapter 3, Sections 3.7.6).

5.5 METHODOLOGY OF THE EMG STUDY

5.5.1 Subjects

Twelve male subjects, aged between 23 and 28 years, participated in the study. All subjects completed a consent form and a questionnaire confirming their fitness for the experiment. 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.

5.5.2 Apparatus

5.5.2.1 Subject environment

Subjects were seated on the same conventional car seat used during the previous subjective studies, with their feet supported on an adjustable footrest. The seat and footrest were fixed on a vibrator platform able to vibrate the seat in the fore-and-aft direction. The headrest was removed from the seat.

5.5.2.2 Generate and acquire the vibration

Motion signals were generated and acquired using *HVLab* software (version 3.81). A computer was used to simultaneously generate the stimuli and acquire the acceleration of the seat. Data were analysed using Matlab software (version R2007a).

Stimuli were produced by a digital-to-analogue converter and reproduced on a horizontal hydraulic vibrator capable of displacements of 1 metre (peak-to-peak). An accelerometer (Entran EGCS-do-10/V10/LM4), located on the platform, was used to acquire the acceleration at 50 samples per second via 30 Hz low-pass filters.

5.5.2.3 Measurement and acquisition of muscle activity

Surface electromyographic, SEMG, electrodes were placed on the necks of the subjects and a reference electrode was located next to the sternum (see Section 5.2.2.2). The electrodes were silver/silver chloride pre-gelled electrodes as recommended by SENIAM

(Hermens *et al*., 2000) for surface electromyographic applications, with an inter-electrode separation of 2 cm (Hermens *et al*., 2000). Noraxon dual electrodes, disposable, self-adhesive, pre-gelled with snap connection were used. The electrodes were connected to a preamplifier (Noraxon TeleMyo 2400T). The system allowed the acquisition of the SEMG signal with wireless transmission to a personal computer. The software used for the acquisition of the SEMG signals was Noraxon MRXP1.06 Master Edition. Data were analysed using Matlab (version R2007a) software.

5.5.3 Experimental design

Each of the twelve subjects participated in three sessions. Each session consisted of a similar procedure: preparation of the skin, placement of the electrodes, measurement of the maximum voluntary contraction (MVC), exposure to one whole-body vibration stimulus for 10 minutes, a break of 15 minutes, and exposure to another whole-body vibration stimulus for 10 minutes. In one of the three sessions was added a control condition where muscle activity was measured without exposure to vibration.

5.5.3.1 Skin preparation

The skin was cleaned with alcohol and the impedance of the skin confirmed to be between 5 and 10 kilohm. The cleaning of the skin was sufficient to obtain acceptable electrode-skin impedance. Shaving or sand-papering of the skin was not necessary.

5.5.3.2 Placement of the electrodes

The electrodes were placed on the neck of the subject to measure the activity of the semispinalis capitis, considered to be the primary extensor, and the most active muscle during exposure to fore-and-aft whole-body vibration (see Section 5.2.3).

The centre of the two active electrodes was localised 2 cm below the occipital bone and 2 cm from the lateral midline (see Figure 5.9). This location has been used by other researchers, as reviewed by Sommerich *et al*. (2000). The third reference electrode was placed over the collarbone where there is no muscle beneath the skin.

5.5.3.3 Measurement of the Maximum Voluntary Contraction

The amplitude of EMG signals can vary greatly between subjects and within subject from day-to-day for the same muscle site. One way of compensating for this variability is to normalize the measured EMG to a reference value. The muscle activity during a maximum voluntary contraction, MVC, was measured to allow normalization of the measured SEMG signal. Using the EMG during a MVC as a reference, signals acquired in different sessions and with different subjects can be compared. The measurement of the MVC also provided

Figure 5.9 Photo of the localisation of the active electrodes on a pilot subject

an opportunity to check the set-up of the electrodes and verify that the system was working. The measurement of the MVC consisted of asking the subjects, after some warming up with motions of the neck, to press as much as they could with their head backwards against a static resistance for a duration of three seconds. This isometric contraction was repeated three times at intervals of 30 seconds.

5.5.3.4 Exposure to whole-body vibration stimuli

After acquiring the EMG during the MVC, subjects sat on the car seat, with the headrest removed. They adopted a comfortable upright posture and were asked to look forward. They were exposed to the first of six stimuli for a duration of 10 minutes. The stimuli consisted of sinusoidal fore-and-aft vibrations at six frequencies (0.5, 1.0, 2.0, 4.0, 8.0 and 16 Hz).

Table 5.2 Characteristics of the vibration stimuli

Direction	Fore-and-aft					
Waveform	Sinusoidal					
Duration [s]	600					
Frequency [Hz]	0.50	1.00	2.00	4.00	8.00	16.00
Floor acceleration [ms^{-2} r.m.s.]	**0.28**	**0.23**	**0.23**	**0.21**	**0.61**	**1.10**

The magnitude of each vibration was calculated using ISO 2631 (International Organization for Standardization, 1997) so as to produce a discomfort equivalent to a 10 seconds, 4 Hz, lateral excitation at 0.5 m.s^{-2} rms. It was assumed that two vibrations of the same duration produce an equivalent level of discomfort if their total weighted r.m.s. accelerations are equal. The total weighted r.m.s. acceleration was calculated from the root-sums-of-squares of the weighted floor acceleration, the weighted seat pan acceleration, and the weighted backrest accelerations, where the weightings included the multiplying factors for these three locations as in ISO 2631-1 (1997). The seat pan and

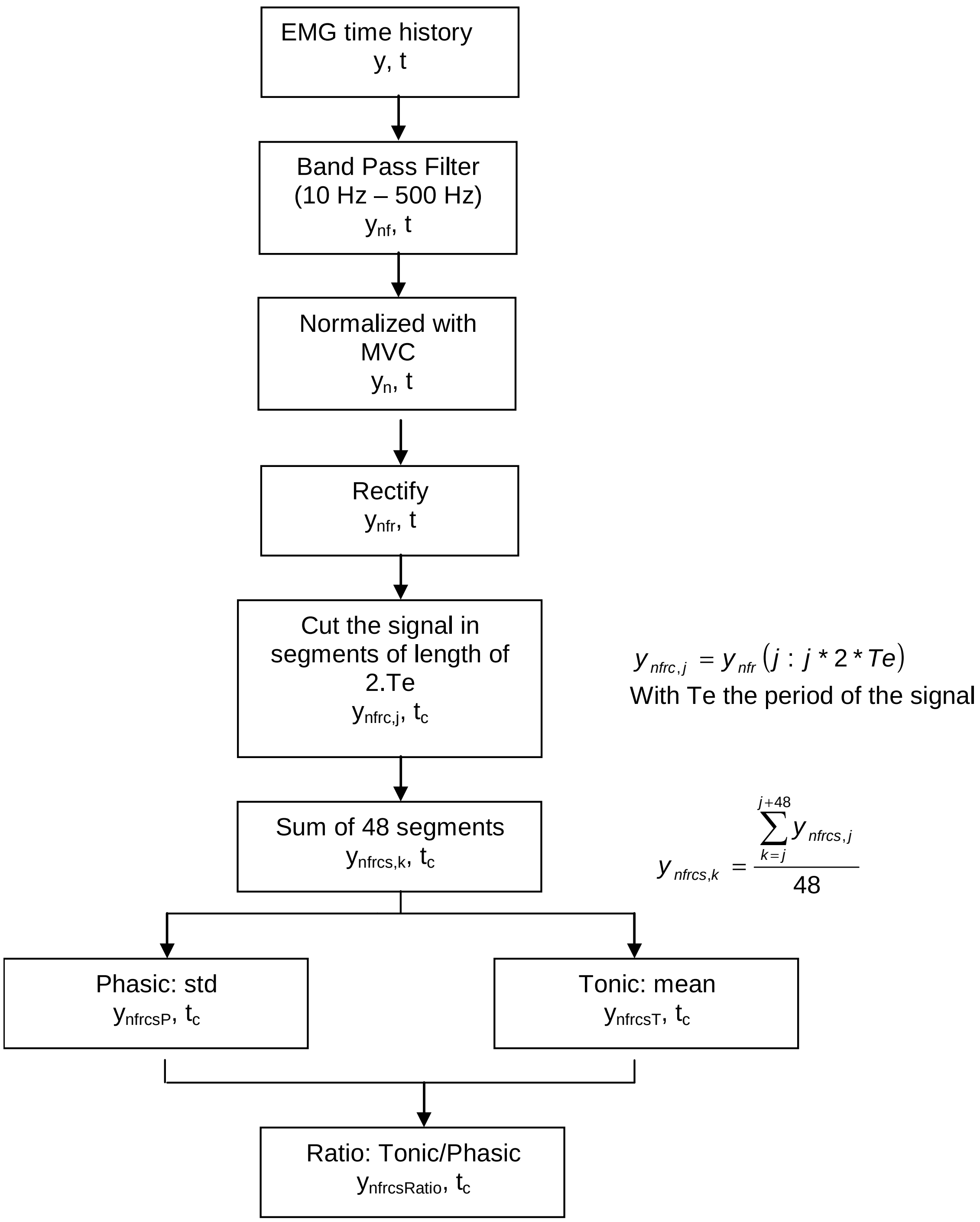


Figure 5.10 Data analysis procedure to calculate the phasic and tonic activity.

backrest acceleration were obtained by multiplying the acceleration at the floor by, respectively, the seat transmissibility and the backrest transmissibility measured previously. All the multiplying factors and frequency weightings used are presented in Chapter 3, Section 3.7.1.2 (Tables 3.2, 3.3 and 3.4). Table 5.2 shows the vibration characteristics, including the calculated magnitudes of the fore-and-aft excitations at the floor. The order of presentation of the stimuli was randomised independently for each subject.

After the first exposure to whole-body vibration, subjects had a rest for 15 minutes. During this break, they were asked to adjust the backrest and use the headrest to adopt a posture in which they could relax their neck muscles. Preliminary studies with two subjects suggested that 15 minutes of rest in these conditions was sufficient to obtain a SEMG signal similar to that before exposure to whole-body vibration. After the 15-minute rest, subjects were exposed to a second stimulus. After the second stimulus they left, returning for further sessions on different days.

5.5.4 Procedure for data analysis

5.5.4.1 Band-pass filtering

The first step in the analysis was to filter the raw SEMG signal. The signal, acquired at 1500 samples per second, was high-pass filtered at 10 Hz to reduce effects of any artefacts due to displacement of the electrode cables. The signal was also low-pass filtered at 500 Hz to reduce noise. The data were band-pass filtered with a digital Butterworth filter with an order 5, using Matlab (R2007a).

5.5.4.2 Normalisation procedure

The EMG from the maximum voluntary contraction (MVC) was then calculated from the band-pass filtered raw SEMG data. The MVC was obtained with a Matlab algorithm using a gliding window of 500 ms duration. For each step of 20 ms, the mean amplitude of the EMG was calculated. The MVC value, used for normalization, was the highest mean amplitude during the 10-second period (Konrad, 2005). The normalization is obtained by divided each band-pass filtered SEMG signal with the corresponding MVC value.

5.5.4.3 SEMG Root Mean Square

The root mean square was calculated form the normalized filtered SEMG signals with an integration time of 6 seconds.

5.5.4.4 Procedure to calculate the phasic and tonic muscle activity

Phasic and tonic activities were calculated from averaged signals. Averaging provides a simple method of improving the clarity of EMG signals and increases the signal-to-noise ratio. Muscle activity is randomly positive and negative in polarity, so if an EMG signal is averaged over time, the positive and negative peaks tend to cancel each other and the average activity decreases towards zero. Therefore, before averaging, the normalized filtered EMG signal was rectified. The rectified EMG was averaged with reference to the period of the vibration excitation. Time histories were averaged with an averaging window having a duration of two cycles of the platform acceleration, there were 48 such epochs in each average.

Figure 5.10 shows how the phasic and tonic activities were calculated from the averaged signals. The phasic activity was defined as the standard deviation of the averaged EMG and the tonic activity was defined as the mean amplitude of the averaged EMG. The phasic activity represents the periodic properties of the signal.

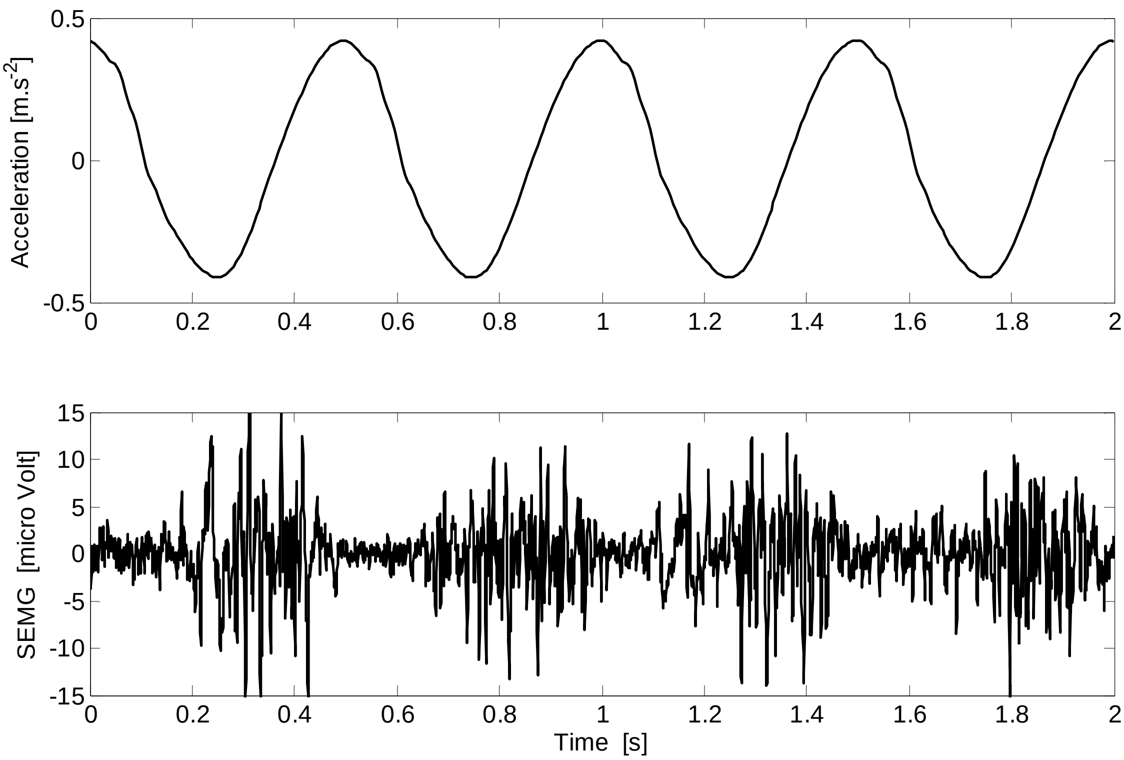


Figure 5.11 Acceleration of the platform (upper) and surface EMG (lower) for a 2.0 Hz, 0.27 $m.s^{-2}$ r.m.s, fore-and-aft excitation.

5.6 RESULTS

5.6.1 Signal averaging

Figure 5.11 shows an example of the filtered acceleration and band-pass filtered EMG data. It is possible to see periodic peaks of activity at a frequency similar to the frequency of vibration excitation. To study the effect of the frequency of excitation on the muscle activity further analysis was performed.

Figure 5.12 shows the averaged rectified SEMG (calculated as described in Section 5.5.4.4) for the same condition used to illustrate the data in Figure 5.11, together with the average of the simultaneously recorded vibrator platform acceleration. This method of signal averaging allows the quantification of any artefact contained in the averages. As mentioned previously, the EMG is random in polarity, and will tend to zero over time if averaged without prior rectification. This property was employed to quantify the contribution of artefacts in the measured EMG signals. The un-rectified SEMG time history was averaged and then this average was rectified. It is unlikely that any artefacts present will be random in polarity and so this processed signal should indicate the part of the

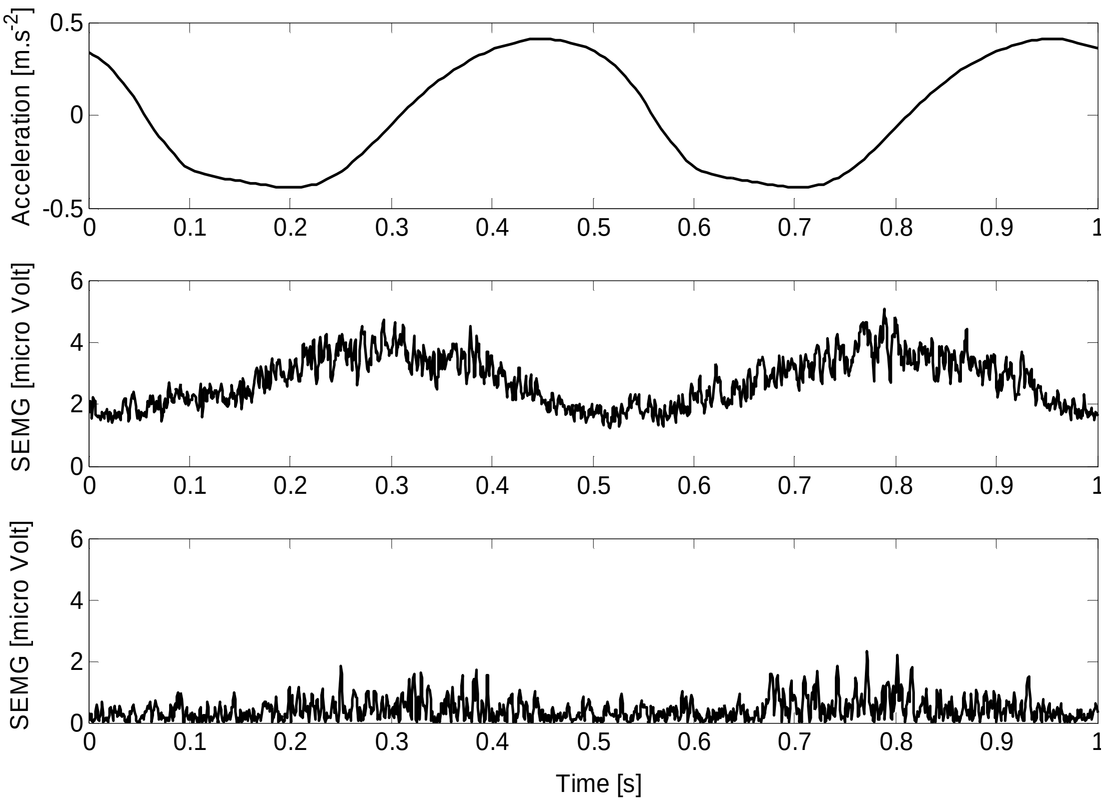


Figure 5.12 Averaged platform acceleration (upper), averaged rectified SEMG (centre) and rectified averaged SEMG (lower) for a 2.0 Hz, 0.27 $m.s^{-2}$ r.m.s, fore-and-aft excitation.

acquired signal which is not of myoelectric origin. The lower part of Figure 5.12 is such a rectified average and indicates the part of the average rectified time history identified as an artefact.

The electrocardiogram (ECG) is an electrophysiological potential that can be picked up by the SEMG electrodes. The observation of the time history SEMG signal acquired during the rest period (while subjects adopted a relax posture between two dynamic stimuli) showed no presence of ECG in the acquired SEMG signal, but this and other activity may have contributed to the artefacts represented in Figure 5.12.

5.6.2 SEMG root-mean-square

The root-mean-square can be used to quantify the magnitude of a varying quantity. Figure 5.13 shows the median values of the variation over time of the r.m.s. value of the normalized band-pass filtered SEMG signals for each frequency of excitation and for the control study (the control study consisted of measuring SEMG signal at the neck with subjects seated on a car seat without headrest, without exposure to vibration). The graph shows no clear effect of the frequency of excitation and no effect of the duration of the vibration exposure on the r.m.s. value of the SEMG signals. A statistical analysis using

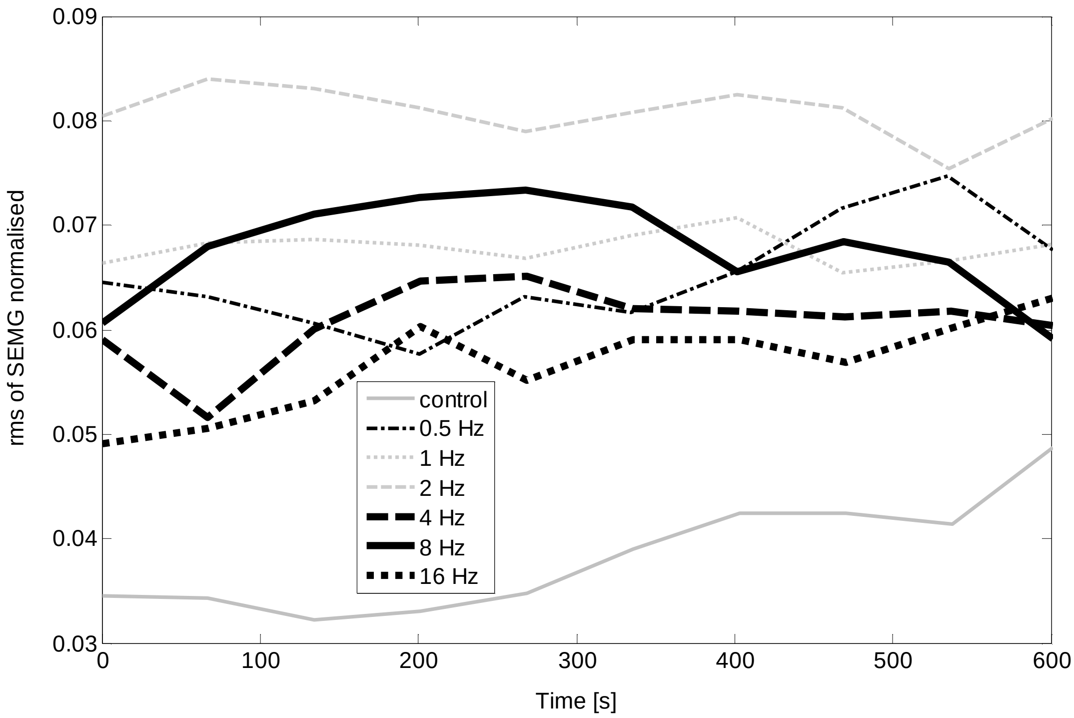


Figure 5.13 Effects of the frequency of the excitation on the r.m.s. SEMG signals measured at the neck (median values).

Friedman tests was conducted at each frequency and with the control study for three points in time (at the beginning, at the 5th minute and at the 10th minute). It showed no significant effect (p>0.05) of the exposure duration on the r.m.s of the SEMG signals (see Table 5.3). A similar analysis was performed at the 10th minute for all frequencies and the control study. Table 5.4 presents the results of the Friedman test and shows significant differences between the conditions. A Wilcoxon matched-pairs signed rank test for two related samples was then used to identify differences between two conditions. Table 5.4 presents the results of the Wilcoxon tests. It shows that being exposed to vibration increased significantly the r.m.s. value of the SEMG. However no effects of the frequency of excitation on the r.m.s. SEMG signals were found.

5.6.3 Phasic and tonic activity

Phasic and tonic activities were calculated according to the signal processing procedure described in Section 5.5.4.4. From the calculated magnitudes of phasic and tonic activity, the effects of frequency were unclear. It is possible that the normalization process using Maximum Voluntary Contraction (MVC) was not suitable for this application. It is probable that the static force applied by the subjects' head and required for the MVC (see Section (5.5.3.3) varied slightly within subject from one session to another. The variation of the maximum contraction applied within subject may affect the comparison of the phasic and tonic muscle activity between frequencies. To eliminate the effect of the MVC normalization process in the study of the effect of frequency on the phasic and tonic activity, each data point of the phasic and tonic signal was divided by the r.m.s. value of the normalized rectified averaged of the SEMG signal such as:

$phasic\_normalized(i) = \dfrac{phasic(i)}{\sqrt{(phasic(i)^2 + tonic(i)^2}}$. This allows a better normalization of the data and a better observation of the phasic and tonic activities contained in the SEMG signal.

Since the overall neck muscle activity is more or less constant (no significant difference in the SEMG signal was found between frequencies), the normalized values of phasic and tonic activity are thought to be more or less proportional to the absolute values. In this chapter, the terms phasic and tonic activities represent the normalized phasic and tonic activities.

Figure 5.14 shows the effects of the frequency of excitation on the normalized phasic and tonic activity at four different points in time (because 48 cycles were required to make an average, not enough cycles were available at 0.5 Hz and 1 Hz to make an average at the 538 s). The figures show that with increasing frequency (from 1 Hz to 16 Hz), the

Table 5.3 Effects of duration on the SEMG r.m.s.

The variables are constructed according to the following: y"frequency"t"duration". For examples yct10 represents the SEMG r.m.s measured during the control study at the 10^{th} minute, y16t0 represents the SEMG r.m.s. measured at the beginning of a 16 Hz vibration exposure.

Ranks	
	Mean Rank
yct0	1,625
yct5	2,083333
yct10	2,291667

Ranks	
	Mean Rank
y05t0	2,25
y05t5	1,666667
y05t10	2,083333

Ranks	
	Mean Rank
y1t0	2,083333
y1t5	1,666667
y1t10	2,25

Test Statistics (a)	
N	12
Chi-Square	3,116279
df	2
Asymp. Sig.	0,210527
a. Friedman Test	

Test Statistics (a)	
N	12
Chi-Square	2,166667
df	2
Asymp. Sig.	0,338465
a. Friedman Test	

Test Statistics (a)	
N	12
Chi-Square	2,166667
df	2
Asymp. Sig.	0,338465
a. Friedman Test	

Ranks	
	Mean Rank
y2t0	2,083333
y2t5	2,083333
y2t10	1,833333

Ranks	
	Mean Rank
y4t0	1,916667
y4t5	2
y4t10	2,083333

Ranks	
	Mean Rank
y8t0	1,75
y8t5	2,25
y8t10	2

Test Statistics (a)	
N	12
Chi-Square	0,5
df	2
Asymp. Sig.	0,778801
a. Friedman Test	

Test Statistics (a)	
N	12
Chi-Square	0,166667
df	2
Asymp. Sig.	0,920044
a. Friedman Test	

Test Statistics (a)	
N	12
Chi-Square	1,5
df	2
Asymp. Sig.	0,472367
a. Friedman Test	

Ranks	
	Mean Rank
y16t0	1,666667
y16t5	2,166667
y16t10	2,166667

Test Statistics (a)	
N	12
Chi-Square	2
df	2

Table 5.4 Effects of the frequency of excitation on the r.m.s. SEMG values. The variables are constructed according to the following: y"frequency"t"duration". For examples yct10 represents the SEMG r.m.s measured during the control study at the 10^{th} minute, y16t0 represents the SEMG r.m.s. measured at the beginning of a 16 Hz vibration exposure.

Ranks	
	Mean Rank
yct10	1,666667
y05t10	3,958333
y1t10	3,916667
y2t10	5,5
y4t10	4,083333
y8t10	5,208333
y16t10	3,666667

Wilcoxon	0.5 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	16.0 Hz
Control	0.023	0.023	0.002	0.008	0.002	0.019
0.5 Hz		0.875	0.117	0.754	0.136	0.583
1.0 Hz			0.084	0.724	0.136	0.638
2.0 Hz				0.060	0.754	0.158
4.0 Hz					0.158	0.530
8.0 Hz						0.084

Test Statistics (a)	
N	12
Chi-Square	23,90164
df	6
Asymp. Sig.	**0,000544**
a. Friedman Test	

normalized tonic activity increased and the normalized phasic activity decreased. A peak in the normalized phasic activity and a drop in the normalized tonic activity can be observed at 1 Hz.

Friedman tests were conducted at each frequency to investigate the effects of duration of exposure on the normalized phasic and tonic activity. Table 5.5 shows that, irrespective of the frequency, duration had no effect on either the normalized phasic or the normalized tonic neck muscle activity.

Similar Friedman tests were conducted at each duration, to investigate the effects of the frequency on the normalized phasic and tonic activity. Table 5.6 shows that frequency affected significantly both the normalized tonic and the phasic activity. Wilcoxon matched-pairs signed ranks tests for two related samples were used to identify differences in the normalized phasic and tonic activity between the different frequencies of excitation at the 384^{th} second of exposure. Table 5.7 shows that 1-Hz excitation produced significantly greater normalized phasic activity and less normalized tonic activity than the other frequencies (except at 2 Hz). Also, 0.5-Hz, 1-Hz, 2-Hz, 4-Hz and 8-Hz excitation generated significantly less normalized phasic and greater normalized tonic activity than the 16-Hz excitation ($p<0.05$).

Figure 5.15 show the median normalized phasic, tonic and ratio of phasic over tonic neck muscle activity measured and calculated at the 384^{th} second of exposure. It also presents

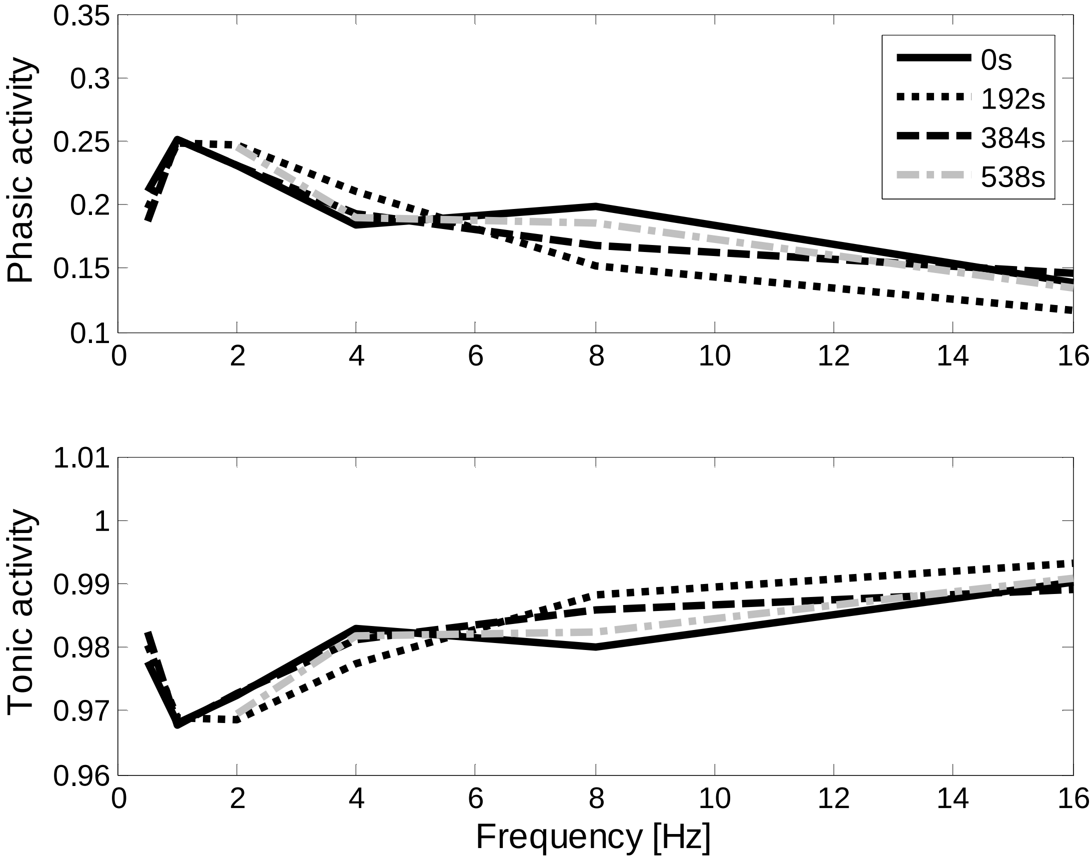


Figure 5.14 Effect of the frequency and the duration of whole-body vibration on the normalized neck muscle phasic and tonic activities (median values).

the inter-subject variability with the 25th and 75th percentile. Inter-subject variability seems to be greater for low-frequencies than frequencies at 8 and 16 Hz. The ratio shows a peak at 1 Hz and decreases as the frequency increases.

5.7 DISCUSSION

5.7.1 Quality of the measured SEMG signals

Figure 5.12 indicates that the SEMG signals contained around 15% of artefact. During preliminary studies, special care was taken to reduce artefacts. The SEMG equipment used was chosen to perform well with low magnitude signals and in noisy electromagnetic environment.

Table 5.5 Effects of the duration on the normalized phasic and tonic neck muscle activity for each frequency. The variables' name presents the frequency then the type of activity, either phasic (ph) or tonic (to) and the duration in second. For example f05ph192 is the phasic activity calculated at the 192nd second of exposure to a 0.5 Hz fore-and-aft sinusoidal excitation.

	PHASIC ACTIVITY					
	0.5 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	16.0 Hz
			f2ph0	f4ph0	f8ph0	f16ph0
	f05ph0	f1ph0	f2ph192	f4ph192	f8ph192	f16ph192
	f05ph192	f1ph192	f2ph384	f4ph384	f8ph384	f16ph384
	f05ph384	f1ph384	f2ph538	f4ph538	f8ph538	f16ph538
Friedman test Asymptotic significance	0.338	0.558	0.475	0.615	0.369	0.062

	TONIC ACTIVITY					
	0.5 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	16.0 Hz
			f2to0	f4to0	f8to0	f16to0
	f05to0	f1to0	f2to192	f4to192	f8to192	f16to0
	f05to192	f1to192	f2to384	f4to384	f8to384	f16to0
	f05to384	f1to384	f2to538	f4to538	f8to538	f16to0
Friedman test Asymptotic significance	0.338	0.558	0.593	0.615	0.102	0.053

5.7.2 Effects of vibration duration on neck muscle activity

In this physiological study an effect of whole-body vibration on localised 'muscle fatigue' was not observed. Figure 5.13 showed no increase of the r.m.s. value of the SEMG signals with increasing exposure duration. This agrees with some studies of back muscles (e.g., Hosea *et al.,* 1986; Zimmermann *et al.,* 1993; De Oliviera and Nadal, 2004). Although it has not been observed here, this does not mean that localised 'muscle fatigue' cannot be generated by vibration. Localised 'muscle fatigue' from vibration can be observed by applying a preload to muscles (e.g., Seidel *et al.,* 1980; Wilder *et al*., 1982; Pope *et al*., 1985; Seroussi *et al.,* 1985; Magnusson, 1991; Hansson, 1991). However, applying a static load or asking subjects to lean their heads forward to preload their neck muscles would have resulted in a posture different from that in which the comfort time-dependencies were obtained. It was desired to measure neck muscle activity with the same conditions used to measure the evolution of discomfort with whole-body vibration.

The exposure duration had also no significant effect on the phasic or tonic activity. Robertson and Griffin (1989) found that tonic activity increased only after 90 minutes of exposure, whereas phasic activity stayed constant over the three hours of exposure. Another mechanism of the muscle, not observed in this thesis, could be activated after very long exposure to vibration.

5.7.3 Effects of vibration frequency on the neck muscle activity

There was no clear effect of the frequency of vibration excitation on the r.m.s. value of the SEMG signal (Figure 5.13). Seidel (1988) found an increase of the r.m.s. value of the SEMG signal (measured from back muscles) with increasing frequency, from 0.315 Hz to 5.0 Hz, of vertical vibration. The vibration acceleration he used was the same at each frequency, whereas in this study the accelerations were calculated to generate similar discomfort during the first 10 seconds of exposure. This difference between the two studies may explain the difference observed in the r.m.s. value of the SEMG signal. It is also possible that the normalization process, using the MVC was not sufficiently accurate to measure small differences between the frequencies. The MVC requires the subjects to press as much as they could with their head backwards against a static resistance. The forces applied by the subjects may have been slightly different between two conditions (two sessions). On this basis, the MVC process may have affected the magnitudes of the normalized EMG signals.

The content of the normalized phasic and tonic activity depends greatly on the frequency of excitation. As the frequency increased, the normalized tonic activity increased and the

Table 5.6 Effects of the frequency of excitation on the normalized phasic and tonic neck muscle activity. The variables' name presents the frequency then the type of activity, either phasic (ph) or tonic (to) and the duration in second. For example f05ph192 is the phasic activity calculated at the 192nd second of exposure to a 0.5 Hz fore-and-aft sinusoidal excitation.

	PHASIC ACTIVITY			
	0 s	**192 s**	**384 s**	**538 s**
	f05ph0	f05ph192	f05ph384	
	f1ph0	f1ph192	f1ph384	
	f2ph0	f2ph192	f2ph384	f2ph538
	f4ph0	f4ph192	f4ph384	f4ph538
	f8ph0	f8ph192	f8ph384	f8ph538
	f16ph0	f16ph192	f16ph384	f16ph538
Friedman test Asymptotic significance	0.000	0.001	0.001	0.005

	TONIC ACTIVITY			
	0 s	**192 s**	**384 s**	**538 s**
	f05to0	f05to192	f05to384	
	f1to0	f1to192	f1to384	
	f2to0	f2to192	f2to384	f2to538
	f4to0	f4to192	f4to384	f4to538
	f8to0	f8to192	f8to384	f8to538
	f16to0	f16to192	f16to384	f16to538
Friedman test Asymptotic significance	0.000	0.000	0.001	0.002

Table 5.7 Effects of the frequency of excitation on the normalized phasic and tonic neck muscle activity (*p* values of data taken at the 384th second)

PHASIC ACTIVITY					
Wilcoxon	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 Hz	0.006	0.075	0.530	0.530	0.028
1 Hz		0.374	0.044	0.010	0.002
2 Hz			0.239	0.034	0.010
4 Hz				0.308	0.023
8 Hz					0.042

TONIC ACTIVITY					
Wilcoxon	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 Hz	0.005	0.075	0.433	0.638	0.028
1 Hz		0.800	0.050	0.010	0.002
2 Hz			0.308	0.023	0.010
4 Hz				0.272	0.019
8 Hz					0.042

normalized phasic activity reduced (from 1 Hz to 16 Hz). It seems that as the frequency increased, the ability of the muscles fibres to respond to the excitation with periodic contraction reduced. A similar conclusion could be drawn with studies investigating the phase relationship between the EMG signal and the platform acceleration (Seidel, 1988; Robertson and Griffin, 1989). These studies found an increasing phase lag as the frequency increases, suggesting that the muscle fibres may not respond fast enough to the excitation.

Seidel (1988) suggested that muscle activity at frequencies less than 1.25 Hz (for back muscles during vertical excitation) is triggered by the otoliths while a stretch reflex influences responses at higher frequencies The muscle activity produced by the muscle reflex could be phasic if the muscle fibres have the time to contract and relax during a vibration cycle. When the vibration frequency does not allow enough time for the muscle fibre to relax, some groups of fibres may be contracted continuously so the muscle will generate more tonic activity and less phasic activity. The minimum contraction time of muscle fibres is thought to be in the order of 60 milliseconds (Freund, 1983; Seidel *et al.,* 1986), which corresponds to a complete cycle of 16 Hz. The minimum contraction time is probably less than a complete cycle. On this basis, the frequency limit is expected to be less than 16 Hz. This means that for vibrations at 16 Hz and higher frequencies, the muscle fibres cannot relax during a cycle. This may explain the results shown in Figures

5.14 and 5.15 where, at 16 Hz, the tonic activity is significantly greater and the phasic activity is significantly less than at the other frequencies of excitation (see Table 5.7).

5.7.4 Relationships between neck muscle activity and whole-body response to vibration

At 1 Hz, Figures 5.14 and 5.15 show a peak in the phasic activity and a drop in the tonic activity. A singularity at 1 Hz has also been observed in biodynamic studies. Paddan and Griffin (1998) have shown a resonance at 1 Hz in the seat-to-head transmissibility for seated subjects during fore-and-aft excitation (see Figure 3.22 in Chapter 3). Similar results have been obtained with the apparent mass. Fairley and Griffin (1989) showed that the apparent mass of subjects exposed to fore-and-aft vibration presented a peak at 1 Hz. (They also showed that the backrest increased the effective mass at all frequencies above 1 Hz). This relationship between whole-body responses to vibration and neck muscle

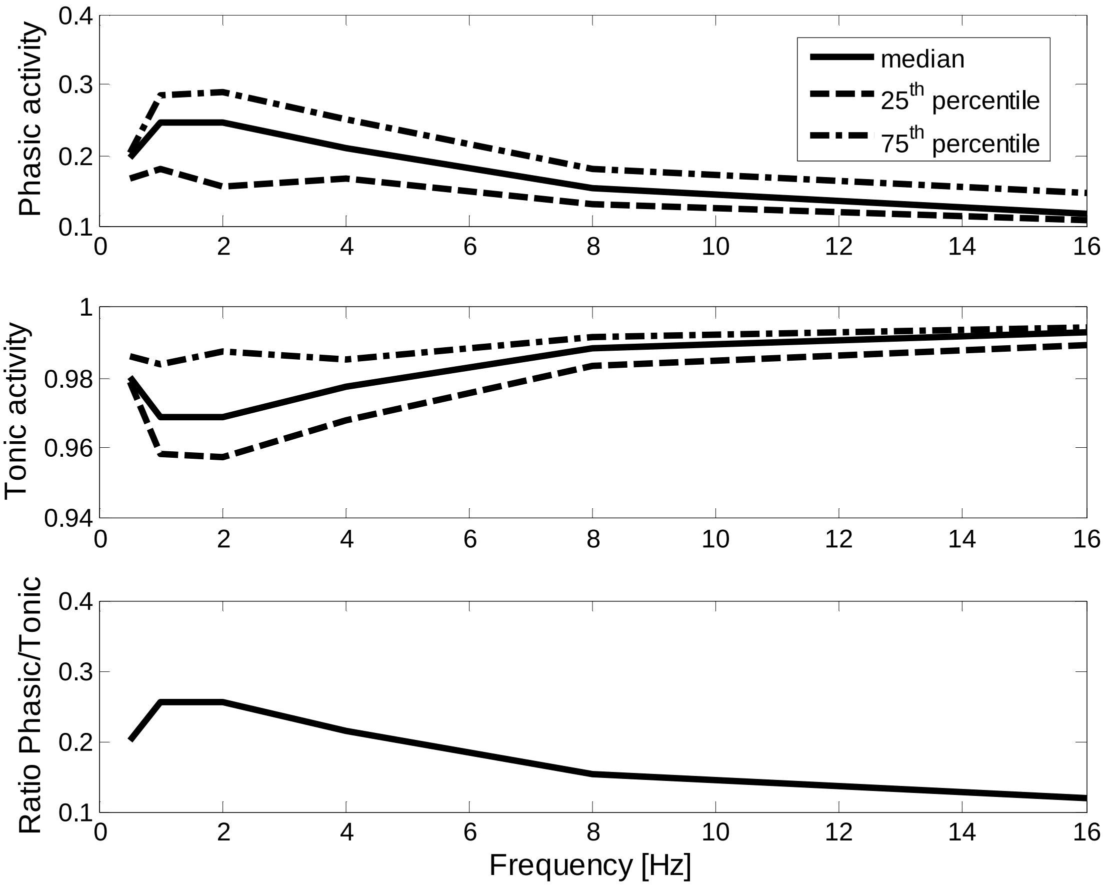


Figure 5.15 Effect of the frequency whole-body vibration on the neck muscle normalized phasic, tonic and ratio phasic/tonic activities (median values).

activity suggests that the type of neck muscle activity produced (ratio of phasic over tonic activity) may be predicted from biodynamic measures (such as seat-to-head transmissibility).

5.7.5 Relationship between subjective discomfort time-dependencies and neck muscle activity

Figure 5.16 compares the subjective discomfort time-dependency (SDTD) curves with the normalized phasic / tonic neck muscle activity ratio. The comfort contour curve was built using the normalized acceleration obtained with fore-and-aft excitation at each frequency studied (see Chapter 3). For 0.5 Hz, the sinusoidal normalized acceleration was taken at the 15th minute of exposure; for 1, 4, 8 and 16 Hz, the narrowband random normalized accelerations were taken at the 30th minute of exposure. The normalized acceleration curve presented in Figure 5.16 is similar to the comfort contour curve measured after 30 minutes of exposure (from 1 Hz to 16 Hz). This means that the selection of lower magnitudes of normalized acceleration correspond to motions that produced greater

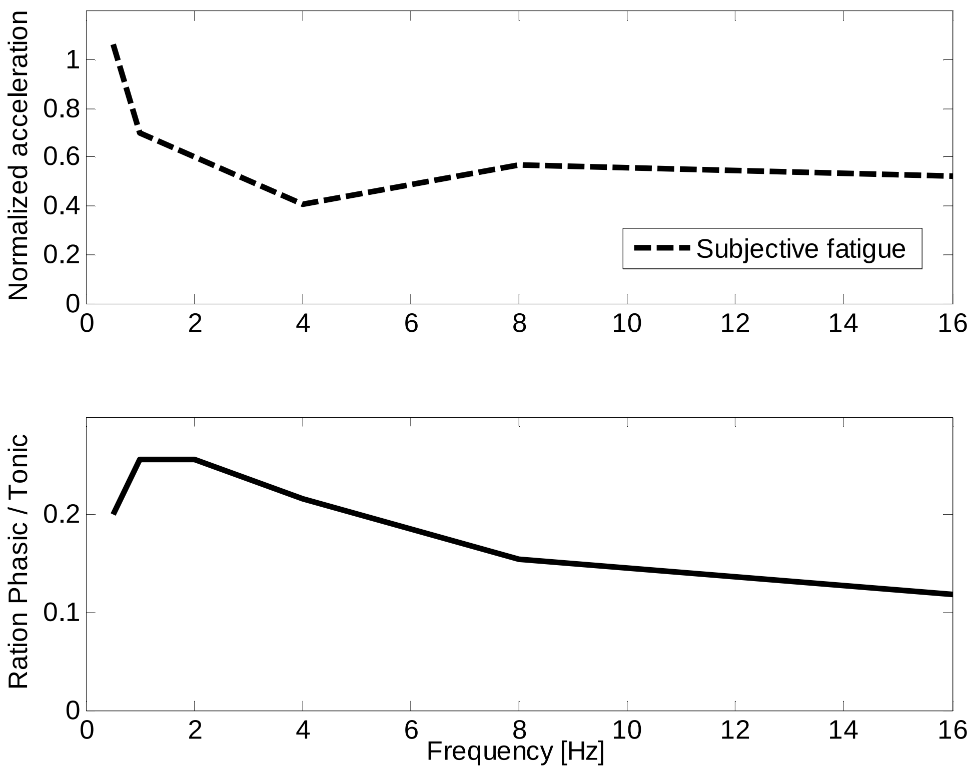


Figure 5.16 Comparison of the comfort countour results obtained in the fore-and-aft direction after 30 minute of vibration exposure with the normalized phasic / tonic neck muscle activity ratio (median values).

SDTD.

The subjective response curve and the normalized phasic / tonic neck muscle activity ratio present similarities and differences. Statistical analyses have been performed in Chapter 3 (Section 3.7.9) to investigate the effects of the frequency of excitation on SDTD. In Section 5.6.2 (Table 5.7) similar analyses have been performed to investigate the effect of frequency on the phasic and tonic activity.

The statistical analyses revealed a singularity at 1 Hz. SDTD was significantly lower at 1 Hz than at 4, 8 and 16 Hz. Normalized phasic activity and tonic activity were significantly, respectively, greater and lower at 1 Hz than at the other frequencies (except at 2 Hz). SDTD may be greater when the muscle fibres are contracted continuously, producing greater tonic activity and less phasic activity. It seems that when the muscle contracts periodically, producing greater phasic activity and less tonic activity, the muscle fibres are not exerting a constant tension and exhibit less 'muscle fatigue' and therefore a lower discomfort time-dependency.

Statistical analyses showed no significant difference between SDTD caused by 16 Hz vibration and SDTD caused by 4 or 8 Hz vibration; whereas the normalized phasic and tonic activity were, respectively, significantly lower and greater at 16 Hz than at all the other frequencies (see Chapter 3, Section 3.7.9 and Table 5.7 of this chapter). According to the statement formulated in the previous paragraph, SDTD should have been greater at 16 Hz than at 4 and 8 Hz. The absolute values of phasic and tonic activity are thought to be more or less proportional to the normalized values. As presented in Section 5.7.3, it is possible that small differences in the overall muscle activity exist between frequencies (due to the MVC process used). On this basis, it could be suggested that the absolute value of the tonic activity at 16 Hz may be similar to the absolute tonic activity at 4 Hz and 8 Hz. With this assumption 4 Hz, 8 Hz and 16 Hz may produce similar SDTD as observed in the subjective studies.

At 0.5 Hz, statistical analyses showed that SDTD was significantly less than at all other frequencies, whereas the normalized phasic and tonic activity were, respectively, only significantly greater and less than those at 16 Hz (see Chapter 3, Section 3.7.9 and Table 5.7 of this chapter).This results does not fit with what was previously stated. If subjective discomfort time-dependency is caused by steady-state tonic activity, 0.5 Hz excitation should have produced less tonic activity (although more phasic activity) than all other frequencies. At 0.5 Hz, the whole body could be considered as rigid, and this may explain the low phasic activity, but it is unclear why the tonic activity was not lower. As discussed for the 16 Hz condition, the absolute value of the tonic activity may have been lower than the one suggested by the normalized value.

5.7.6 Conclusion

For most conditions, SDTD becomes greater with an increase in the tonic activity of muscles and so, since the overall muscle activity is more or less constant, with a decrease in the phasic activity of muscles. Phasic activity represents a periodical contraction of the muscle fibres, whereas tonic activity represents a permanent contraction of the muscle fibres. It seems reasonable to suggest that phasic activity generates lower SDTD than tonic activity because the muscle fibres can relax during a cycle. Muscle fatigue is therefore reduced and discomfort increases at a lower rate.

It was assumed that, since the overall muscle activity is more or less constant for all frequencies, the normalized phasic and tonic activity (normalization performed relative to the overall muscle activity) is more or less proportional to the absolute value of the phasic and tonic activity (see Section 5.6.3). It was suggested that the normalization process used for the SEMG signals with the maximum voluntary contraction, MVC, was not sufficiently refined to observe small effects of the frequency of vibration on the r.m.s. of the SEMG signals. Small variations, between frequencies, of the overall neck muscle activity imply that comparing (between frequencies) the absolute phasic and tonic activity with the normalized phasic and tonic activity might not be suitable. This may explain the cases at 0.5 Hz and 16 Hz where the normalized tonic activity and the SDTD did not fit the overall results suggesting that SDTD increases with the magnitude of the tonic neck muscle activity (see Section 5.7.5).

Different types of neck muscle activity may be associated with different types of head motion. Seat-to-head transmissibility might estimate the type of neck muscle activity produced (e.g., at 1 Hz the peak of in the normalized phasic activity and the reduction in the normalized tonic activity may correspond to a resonance in the seat-to-head transmissibility, see Section 5.7.4).

5.8 CONCLUSION

The process used to normalize the SEMG signals with the Maximum Voluntary Contraction (MVC) allowed reducing the variability of the neck muscle activity measured within subjects and within sessions. It allowed observing a significant difference between the overall neck muscle activity produced during exposure to vibration than without vibration exposure. It was suggested that the MVC process may not be suitable to observe small changed of the phasic and tonic neck muscle activity between frequencies. The *phasic and tonic neck muscle activities were normalized relative to the corresponding r.m.s. values of the neck muscle activity. This second normalization cancelled any possible effect of the MVC process on the magnitudes of the normalized phasic and tonic activity. However information on the absolute values of phasic and tonic activities is lost. Because the overall neck muscle activity was more or less constant between frequencies, it was suggested that the normalized phasic and tonic activities are more or less proportional to their absolute magnitudes.*

An effect of the frequency of fore-and-aft whole-body vibration excitation was observed in SEMG signals at the neck when using an averaging method to distinguish between normalized tonic and normalized phasic muscle activity. With increasing frequency of excitation (from 1 Hz to 16 Hz), the normalized phasic activity decreased, and therefore the normalized tonic activity increased. A peak in the normalized phasic activity corresponding to a drop in the normalized tonic activity observed at 1 Hz may be associated with a resonance in the seat-to-head transmissibility during fore-and-aft excitation. The frequency and the duration of whole-body vibration did not affect the overall r.m.s. value of the SEMG signals. It seems that discomfort increased at a faster rate with motions producing higher tonic activity and lower phasic activity. It was suggested that the magnitude of the tonic activity (representative of a continuous contraction of the muscle fibres) may represent ‘muscle fatigue’ and therefore estimate the subjective discomfort time-dependency.

6 TRANSMISSIBILITY STUDIES

6.1 INTRODUCTION

Subjective studies (Chapter 3) have found that different frequencies of excitation produce different subjective discomfort time-dependencies (SDTD). They also showed that dynamic discomfort was mainly localized at the neck. Physiological studies (Chapter 5) found that SDTD may be proportional to the ratio of phasic neck muscle activity to tonic neck muscle activity. It was also discussed that the magnitude of the absolute tonic activity produced by different frequencies of excitation could play a role in the rate at which discomfort increases with vibration duration (see Chapter 5, Section 5.7.5).

Phasic muscle activity measured at the neck may arise from periodic motions of the head. Tonic muscle activity represents the muscle activity needed to respond to a static load and may be produced to reduce head motions. It is reasonable to suggest that different types of neck muscle activity generate different head motions. Identifying the type of head motions that is responsible for either high phasic or high tonic muscle activity would provide a useful tool to predict SDTD.

Head motions caused by exposure to whole-body vibration are usually evaluated from the seat-to-head transmissibility with subjects seated on a rigid seat (Paddan and Griffin, 1996). Seat-to-head transmissibility compares the head motion relative to the seat acceleration. Engineers will probably be interested to be able to predict head motions and SDTD from acceleration at the floor and the dynamic properties of the seat. For the purpose of such a model, floor-to-head transmissibility and seat transmissibility have been measured (and used in Chapter 7). Floor-to-head transmissibility represents head motion relative to the vibrator platform acceleration. The relationship between neck muscle activity and head motions observed in transmissibility results should involve the neck muscle. The backrest-to-head transmissibility seems to be more suitable than the floor-to-head ttransmissibility to study the relationship between SDTD, neck muscle activity, and head motions. The objectives of this chapter are to investigate whether the backrest-to-head transmissibility can be estimated from the floor-to-head transmissibility and the dynamic properties of the car seat, then to investigate the relationship between the backrest-to-head transmissibility and the SDTD (through the neck muscle activity).

The next section introduces some of the relevant previous work conducted on seat transmissibility and seat-to-head transmissibility. The chapter then presents an experiment where floor-to-head transmissibility and seat transmissibility were measured with subjects seated on a car seat and exposed to sinusoidal, narrowband, and broadband random fore-and-aft excitations. The relationship between the results of subjective studies, physiological studies, and backrest-to-head transmissibility studies is then discussed. The pertinence of a dynamic model of the response of the head and neck in predicting SDTD is introduced.

6.2 TRANSMISSIBILITY BACKGROUND

6.2.1 Transmissibility

Transmissibility is a tool that can be used to understand the dynamic mechanisms of a complex system. Vibration transmissibility consists of comparing the acceleration at one point of a structure (input) with the acceleration at another point (output). Vibration transmitted through the structure reflects the dynamic properties of the system. If the transmissibility is greater than unity, the vibration transmitted from the input to the output is amplified by the structure. If the transmissibility is less than unity the structure attenuates the vibration. The dynamic properties of a system can be described in terms of mass, stiffness and damping. A system can be composed of multiple independent systems, called degrees of freedom, each system having its own mass, stiffness and damping. A one degree of freedom system will resonate (amplify most the transmitted vibration) at the frequency defined by the square-root of the ratio stiffness over mass. The damping will affect the magnitude of the vibration transmitted at the resonance frequency.

6.2.2 Seat transmissibility in the literature

Seat transmissibility is measured by comparing the acceleration at the interface between the seat surface and the human body with the acceleration measured at the base of the seat.

The transducer located on a seat must not alter the dynamic properties of the seat or the natural posture of the seat occupant. Some specific systems are used as the SAE pad or SIT-BAR (see Figure 6.1).

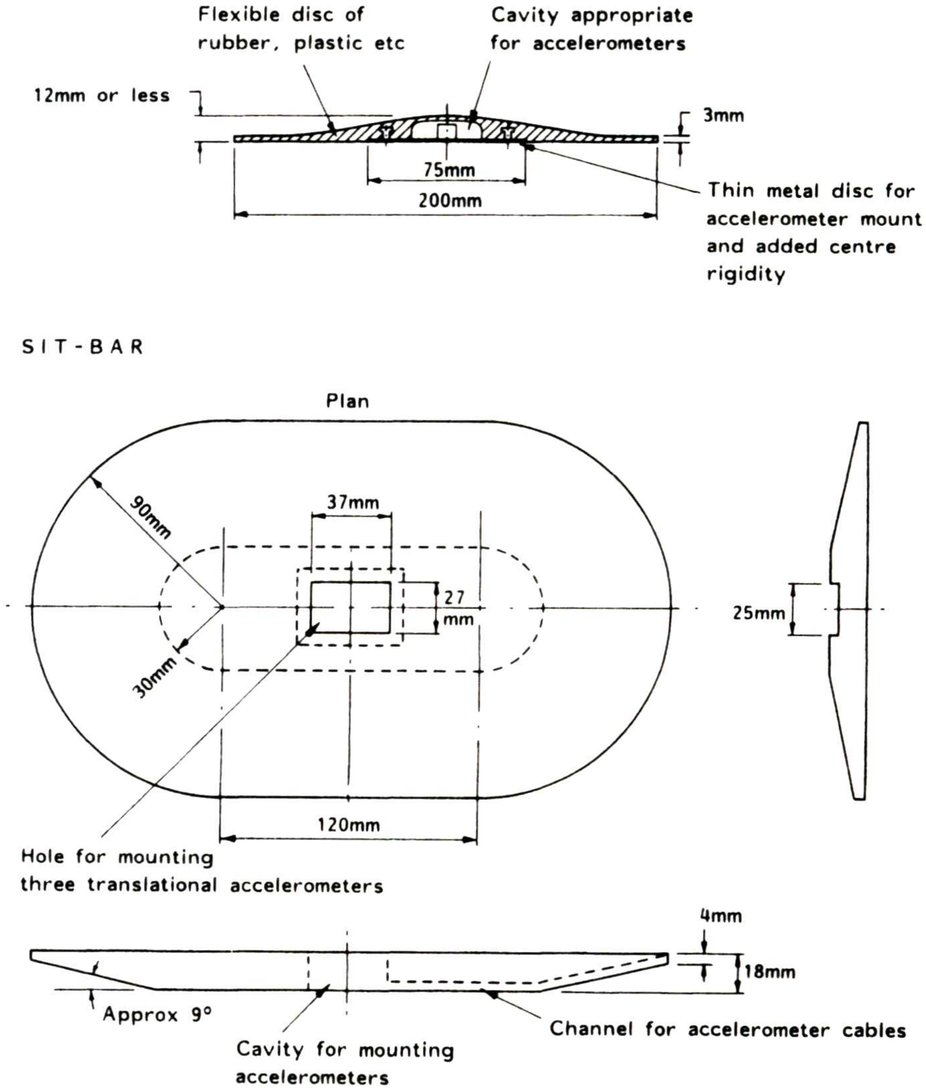


Figure 6.1 Alternative accelerometer mounts for measuring vibration on soft seats. SAE pad from the Society of Automotive Engineers (1974); SIT-BAR from Whitham and Griffin (1977); the SIT-Bar can also be used for measuring rotational vibration.

Seat transmissibility can be measured in any axis (e.g. vertical or horizontal) and to any point (e.g. beneath the ischial tuberosities or between the human back and the seat backrest). Exciting a seat in one direction may produce vibration in more than one direction and even affect the transmissibility in another axis (Fairley, 1984). Similarly, vibration measured on a seat in one direction may be caused by a combination of vertical and horizontal excitations at the floor (Qiu and Griffin, 2004). A seat is therefore a complex structure having multiple degrees of freedom that can be modelled as a multiple-input multiple-output system. Considering a seat transmissibility solely in the direction of excitation gives a limited representation of the dynamic properties of the seat. For fore-and-aft excitation, a study from Nawayseh and Griffin (2005) concluded that both vertical and fore-and-aft responses of the backrest should be taken into account. Transmissibilities measured with fore-and-aft excitation on conventional car seats have shown that a typical backrest resonates around 4 to 5 Hz whereas the seat pan has a near flat response (Qiu and Griffin, 2004; Jalil and Griffin, 2006).

Seat transmissibility can be affected by the vibration magnitude, the location of the points of measurement (for both input and output) and subject posture. Seat transmissibility has been found to be non-linear with the excitation magnitude (Fairley, 1986; Qiu and Griffin, 2003). The resonance frequencies and the peak transmissibility at resonance change with vibration magnitude. Resonance frequencies and the transmissibility at resonance reduce with increasing excitation magnitude. For field measurements, due to excitations in the pitch and roll directions, the location of the sensor at the seat base will affect the measurement of the vibration input and therefore affects the seat transmissibility (Qiu and Griffin, 2004). Backrest transmissibility may also be affected depending on the height of the sensor mounted on the seat backrest (Jalil and Griffin, 2006, 2007). Subjects may also affect the seat transmissibility but some factors can be less important than might be expected. Several studies (e.g. Fairley, 1986; Corbridge *et al.*, 1989; Mansfield and Griffin, 2002) have provided evidence that subject mass has only a small effect. Fairley (1986, 1988) and Jalil and Griffin (2006) showed that backrest contact and angle, and the inclination of the seat pan may have some effect on the seat transmissibility. Corbridge (1987) found that resting the arms on an armrest tended to increase the frequency of resonance. Messenger (1988) found that a lumbar support increased the transmission of vibration from seat to head. In order to reduce variability in the measurements of seat transmissibility, it seems critical to control subject posture during experiments.

6.2.3 Seat-to-head transmissibility in the literature

The transmissibility of the human body reflects various biodynamic responses of the body between the point at which the vibration enters the body and the point at which the vibration is measured on the body. Studies of seat-to-head transmissibility have been reviewed by Paddan and Griffin (1998) who showed there were large differences between the results of the published studies.

Seat-to-head transmissibility can be affected by many factors. Muscle tension and posture are the main sources of intra-subject variability (Griffin, 1975; Griffin *et al.*, 1979; Cooper, 1986; Messenger and Griffin, 1989; Magnusson *et al.*, 1993). Differences in posture and muscle tension can arise both within a subject and between subjects; therefore all sources of intra-subject variability are also sources of inter-subject variability. The additional

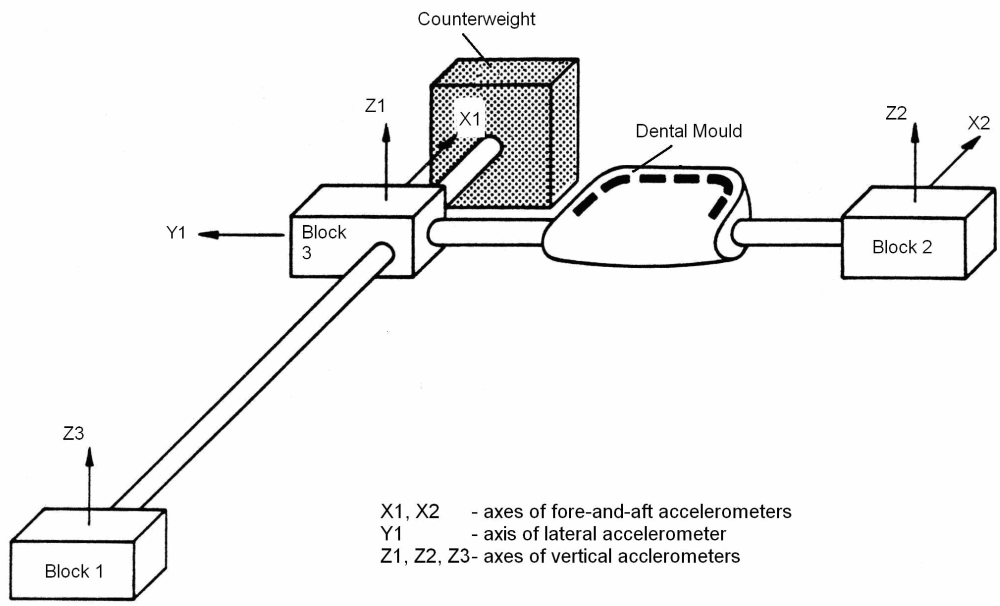


Figure 6.2 The bite-bar used to measure head motions in the study by Paddan and Griffin (1988).

sources of biodynamic differences between subjects relate mainly to the differences in gender (Griffin and Whitham, 1978, Griffin *et al*., 1982) and anthropometric characteristics (e.g. stature and weight) (Griffin and Whitham, 1978; Messenger and Griffin, 1989). The body support (presence of a backrest, inclination of a backrest, head-rest, harness) can also affect seat-to-head transmissibility (Brett, 1990, 1991; Paddan and Griffin, 1988). Experimental arrangements should be well documented because the location of the input vibration and the location of the measurements on the body are critical for the transmissibility measured (Paddan, 1990; Paddan and Griffin, 1993). The type of input motion (vibration magnitude, waveform, etc.) can also affect the transmission of vibration to the head (Griffin *et al.*, 1979).

Seat-to-head transmissibility can be measured with bite-bars. A bite-bar is composed of accelerometers mounted on two perpendicular bars. Subjects generally bite on a mould to have a rigid connection between the accelerometers and the head. Accelerometers are arranged in order to measure fore-and-aft, lateral, vertical, pitch, yaw and roll accelerations. Figure 6.2 shows an example of a bite-bar.

Seat-to-head transmissibility has mainly been measured with subjects seated on rigid seats. Few studies have measured seat-to-head transmissibility with conventional car seats. This study investigates the effects of the seat dynamic properties on the seat-to-head transmissibility.

6.2.4 Experimental seat-to-head transmissibility data (from Paddan and Griffin, 1996)

The study from Paddan and Griffin (1988) is described in detail because the data provided in their experiment are used in this chapter, to compare transmissibility obtained on a rigid seat and on a car seat, and in Chapter 7 for modelling purposes. The data came from a study of intra-subject variability. A brief summary of their procedure is provided below.

The subject who took part in the intra-subject variability study was 38 year old male, 1.85 m in stature and weighing 80 kg. The subject was instructed to avoid voluntary movements to the head during exposure to vibration and to look at a cross marked on a stationary wall in front of him.

They used six accelerometers mounted on a bite-bar to measure six axes of head motion. The rotational accelerations were determined from signals provided by pairs of translational accelerometers. The bite-bar is shown in Figure 6.2.

The translational accelerations of the head were measured by three mutually perpendicular accelerometers on block 3 (i.e. A_{x1} for x-axis, A_{y1} for y-axis, A_{z1} for z-axis). The rotational accelerations were obtained with:

roll acceleration $$r_x = \frac{A_{z2} - A_{z1}}{d_y}$$

pitch acceleration $$r_y = \frac{A_{z3} - A_{z1}}{d_x}$$

yaw acceleration $$r_z = \frac{A_{x2} - A_{x1}}{d_y}$$

where: A_{x1}, A_{x2} ,A_{z1}, A_{z2}, are A_{z3} are accelerations in various axes at different locations and d_x and d_y are distances between accelerometers on blocks 1 and 3 and between blocks 2 and 3, respectively.

The input acceleration measured on the seat at the seat-person interface had a nominally flat constant bandwidth spectrum up to 16 Hz with a duration of 60 seconds and an amplitude of 1.75 ms^{-2} r.m.s.

Measurements were conducted with a rigid seat with the supporting surface of the seat 480 mm above the vibrator platform and inclined backwards at an angle of 3 degrees to the horizontal. The rigid backrest was inclined rearwards at an angle of 6 degrees to the vertical. A 3-mm layer of high stiffness, high friction rubber was glued to surfaces of both the seat and the backrest to reduce relative movement between the subject and the seat due to sliding.

Transfer functions between input acceleration (at the seat) and the output accelerations (at the head) were calculated using the estimator H_1:

$$H(f) = \frac{G_{xy}(f)}{G_{xx}(f)}$$

Where, $G_{xy}(f)$ is the cross-spectrum of the input and output accelerations, and $G_{xx}(f)$ is the power spectrum of the input acceleration.

Figure 6.3 shows the modulus of the seat-to-head transmissibility taken from the first measurement run in the intra-subject variability study – Figure 1 in the paper by Paddan and Griffin (1988). The transfer functions show that the head responded mainly in the mid-sagittal plane (i.e. accelerations in the lateral, roll and yaw axes were relatively small).

Two main resonances are seen for fore-and-aft head motion, one around 1 Hz, and a broad peak near 8 Hz. Vertical and pitch head transmissibility shows a peak around 7 Hz.

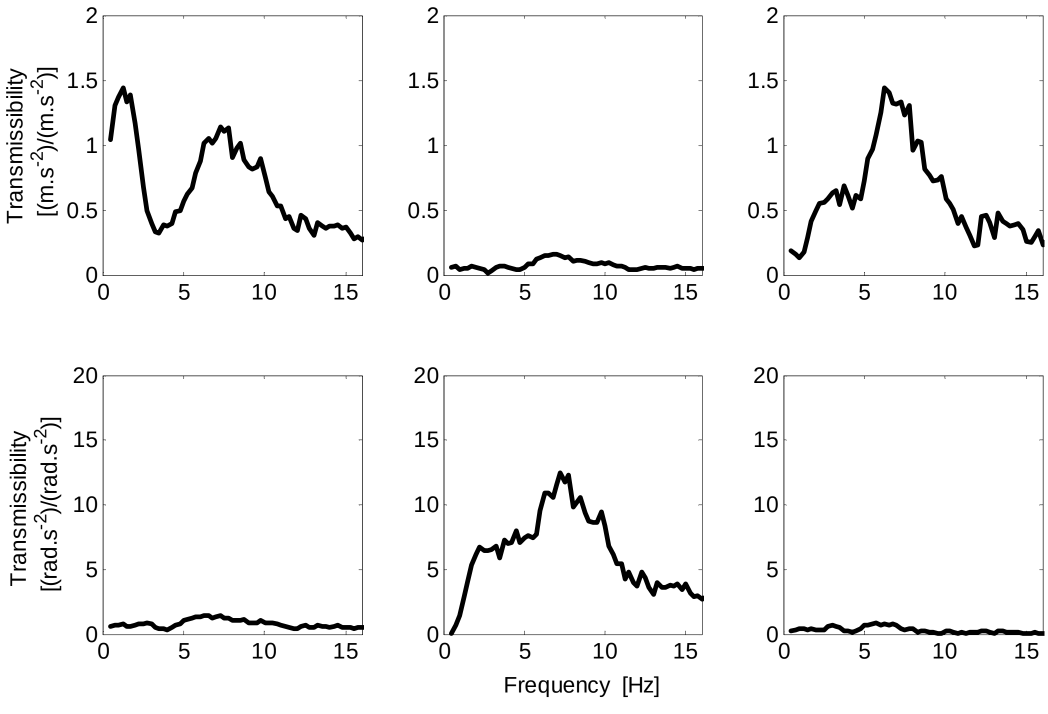


Figure 6.3 Seat-to-head transmissibility obtained with one subject with a broadband random fore-and-aft excitation at 1.75 m.s^{-2} rms. Data from Paddan and Griffin (1988).

6.3 HYPOTHESIS OF THE TRANSMISSIBILITY STUDIES

Subjective studies (see Chapter 3) have shown that the subjective discomfort time dependency (SDTD) depends on the frequency of excitation and the change in discomfort at the neck. Physiological studies (see Chapter 5) found that SDTD tended to be proportional to the ratio of phasic neck muscle activity to tonic neck muscle activity.

It was hypothesised that the transmission of the vibration from the floor to the seat and to the head would improve understanding of the phenomena observed in the neck muscle activity.

According to the literature, it was expected to see head motions depending greatly on the frequency of whole-body vibration. It was also expected that in the fore-and-aft direction the backrest of a car seat would affect significantly the seat-to-head transmissibility.

Because no effect of the waveform on SDTD was observed in the fore-and-aft direction (see Chapter 3), it was also hypothesised that narrowband random vibration and sinusoidal vibration would produce similar floor-to-head transmissibility.

6.4 OBJECTIVE OF THE TRANSMISSIBILITY STUDIES

The discomfort time-dependency seems to be associated with the type of neck muscle activity (see Chapter 5). According to these results, head motions that generate low phasic activity and high tonic activity produce greater SDTD. Predicting the head motion may therefore be useful for predicting SDTD.

The main objective of the study was to measure the head motions to understand the variations observed in the neck muscle activity relative to the frequency of excitation.

The second objective is to investigate the possible means of predicting the floor-to-head transmissibility and the corresponding backrest-to-head transmissibility.

Floor-to-head and seat transmissibility will be used in Chapter 7 to adjust the parameters of a biodynamic model designed to predict floor-to-head and backrest-to-head transmissibility and provide the corresponding mode shapes. Chapter 7 and Chapter 8 will present the model as a tool to estimate SDTD.

6.5 METHODOLOGY OF THE EMG STUDY

6.5.1 Subjects

Twelve male subjects (who already participated in the physiological studies), aged between 23 and 28 years, participated in the study. All subjects completed a consent form and a questionnaire confirming their fitness for the experiment. The experiment was

Table 6.1 Stimuli used for seat and seat-to-head transmissibility

SINUSOIDAL STIMULI		
Frequency [Hz]	Duration [s]	Magnitude [m.s^{-2} rms]
0.5	192.00	0.28
0.63	152.00	0.28
0.79	122.00	0.28
1.00	96.00	0.23
1.26	76.20	0.23
1.59	60.40	0.23
2.00	48.00	0.23
2.52	38.10	0.22
3.17	30.30	0.21
4.00	24.00	0.21
5.04	19.00	0.31
6.35	15.10	0.56
8.00	12.10	0.61
10.00	9.60	0.78
12.70	7.56	0.92
16.00	6.00	1.10

NARROWBAND RAMDOM STIMULI		
Frequency [Hz]	Duration [s]	Magnitude [m.s^{-2} rms]
1.00	96.00	0.23
2.00	48.00	0.23
4.00	24.00	0.21
8.00	12.10	0.61
16.00	6.00	1.10

BROADBAND RAMDOM STIMULI		
Frequency [Hz]	Duration [s]	Magnitude [m.s^{-2} rms]
0.50 - 16.00	180.00	0.30
		0.60
		0.80

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

6.5.2 Apparatus

6.5.2.1 Subject environment

Subjects were seated on the same conventional car seat used during the previous subjective and physiological studies, with their feet supported on an adjustable footrest. The seat and footrest were fixed on a vibrator platform able to vibrate the seat in the fore-and-aft direction. The headrest was removed from the seat. Backrest angle and seat height were similar to the experimental set-up used by Paddan and Griffin (1988) for a rigid seat (see Section 6.2.4).

6.5.2.2 Generate and acquire the vibration

Motion signals were generated and acquired using *HVLab* software (version 3.81). A computer was used to simultaneously generate the stimuli and acquire the acceleration at the floor, the seat and at the head of the subject. Stimuli were produced by a digital-to-analogue converter and reproduced on a horizontal hydraulic vibrator capable of displacements of 1 metre (peak-to-peak). Both motion signals and accelerations were low pass filtered at 40 Hz with analogical elliptic filters.

6.5.2.3 Measurement of seat, floor and head acceleration

An accelerometer (Entran EGCS-do-10/V10/LM4), located on the platform, was used to acquire the floor acceleration at 200 samples per second via 40 Hz low-pass filters.

The accelerations at the interface between the seat-pan and the subjects and between the backrest and the subjects were measured by two seat pads.

The acceleration of the head was measured using a bite-bar mounted with three piezo-resistive accelerometers (see Figure 6.2). An accelerometer measured the fore-and-aft acceleration and two accelerometers measured the vertical acceleration. This arrangement allows the measurement of the fore-and-aft, vertical and pitch accelerations.

Data were analysed using Matlab software (version R2007a).

6.5.3 Stimuli

Sinusoidal, narrowband random, and broadband random waveforms were used in the fore-and-aft direction. The waveform, the frequency, the duration and the magnitude of each stimulus are presented in Table 6.1.

The magnitude of each vibration was calculated using ISO 2631 (International Organization for Standardization, 1997) so as to produce a discomfort equivalent to 10 seconds of 4 Hz, lateral excitation at 0.5 $m.s^{-2}$ r.m.s. It was assumed that two vibrations of the same duration produce an equivalent level of discomfort if their total weighted r.m.s. accelerations are equal. The total weighted r.m.s. acceleration was calculated from the root-sums-of-squares of the weighted floor acceleration, the weighted seat pan acceleration, and the weighted backrest accelerations, where the weightings included the multiplying factors for these three locations as in ISO 2631-1 (1997). The seat pan and backrest acceleration were obtained by multiplying the acceleration at the floor by, respectively, the seat transmissibility and the backrest transmissibility measured previously. All the multiplying factors and frequency weightings used are presented in Chapter 3, Section 3.7.1.2 (Tables 3.2, 3.3 and 3.4.). For the sinusoidal and narrowband random stimuli, the durations of the stimuli were chosen to acquire 96 cycles of the motions.

Because the subjective and physiological studies used different magnitudes of excitation at different frequencies, three magnitudes of broadband random vibration were used: 0.3, 0.6 and 0.8 $m.s^{-2}$ r.m.s.

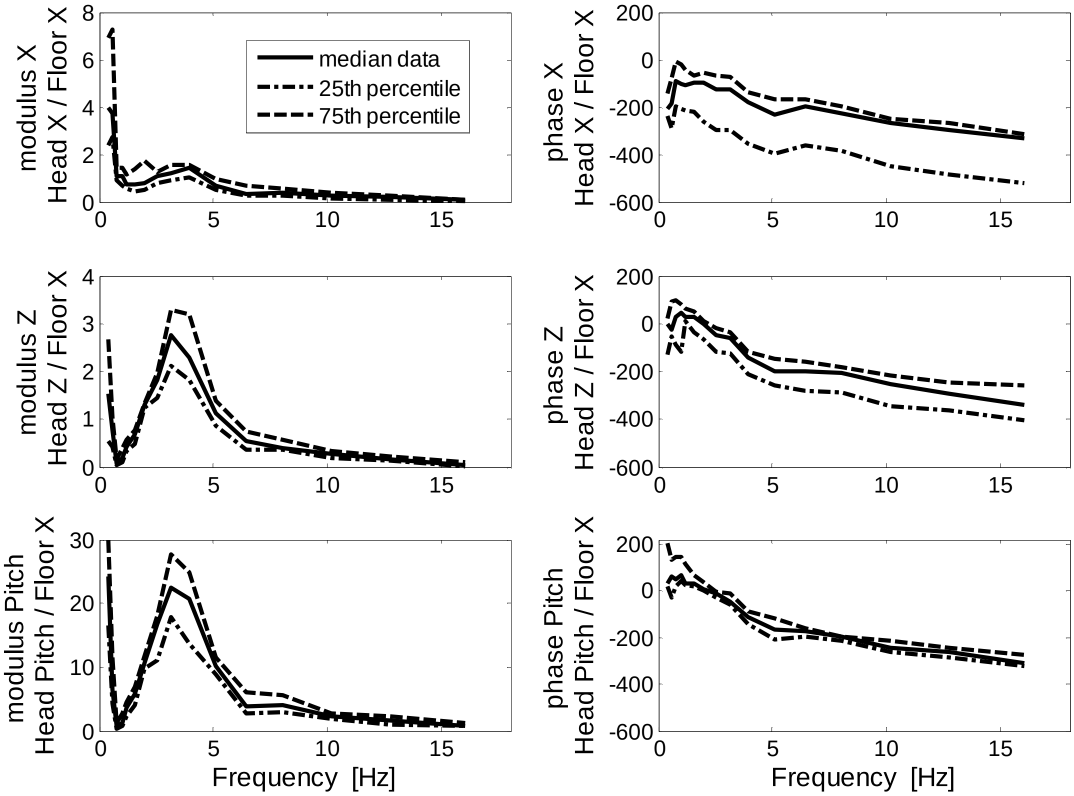


Figure 6.4 Floor-to-head transmissibility obtained with sinusoidal fore-and-aft excitation.

6.5.4 Procedure for data analysis

The analysis of the floor, seat and head accelerations was performed according to the following procedure.

For each subject:

- Data were imported from HVLab to Matlab software.
- Each file was band-pass filtered with a 6^{th} order Butterworth filter between 0.4 Hz and 40 Hz.
- The transfer functions were calculated with the Matlab function *"tfestimate"*. This function calculates the transfer function estimate H_{xy} with x the input signal (floor acceleration) and y the output signal (seat and head acceleration). The relationship between the input x and output y is modelled by the linear, time-invariant estimator H_1 (optimized for noise on the output) expressed by the quotient of the cross power

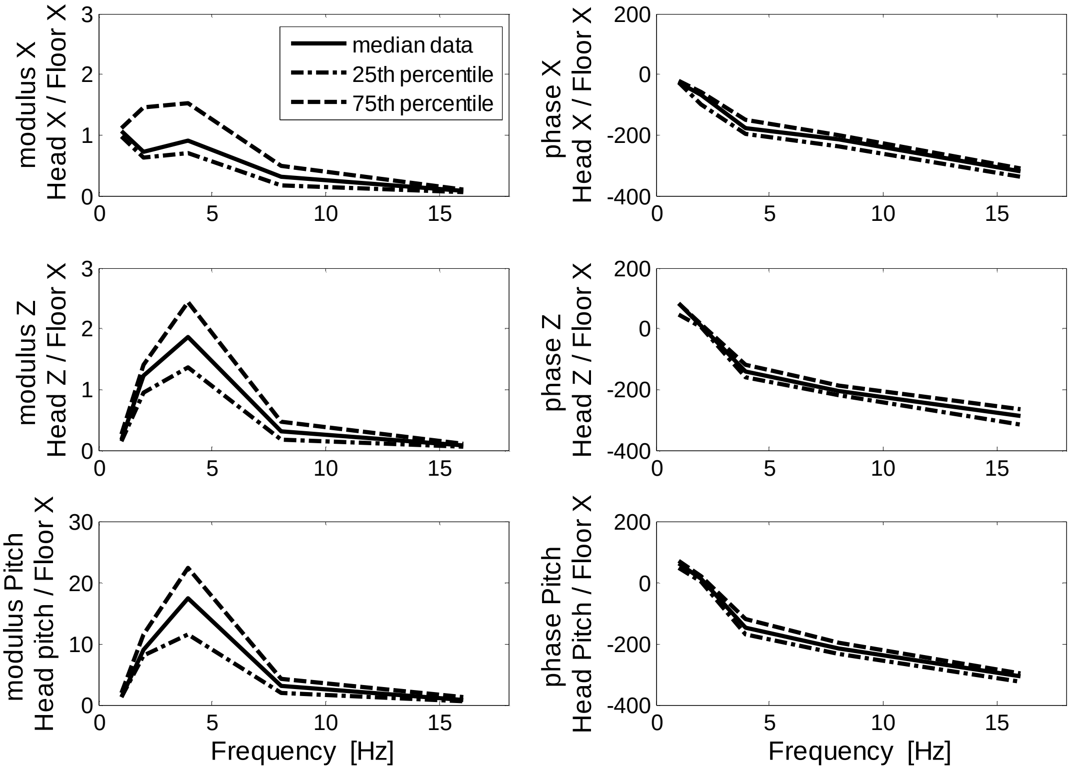


Figure 6.5 Floor-to-head transmissibility obtained with narrowband random fore-and-aft excitation.

spectral density (G_{xy}) of x and y and the power spectral density (G_{xx}) of x: $H_{xy}(f) = \frac{G_{xy}(f)}{G_{xx}(f)}$. The transfer function is calculated with a Hamming window and a 50% overlap. For the spectrum calculated from sinusoidal and narrowband random input signals, only the data point at the frequency of excitation was saved. The spectrum was then recomposed from these single data points.

- From the complex data calculated with the function *"tfestimate"*, the modulus and the phase of the transmissibility were calculated. The phase has to be "unwrap" to allow a continuous reading of the phase for the calculation of the median.

Then the transmissibility data of each subject were used to calculate the median, the 25th and 75th percentile.

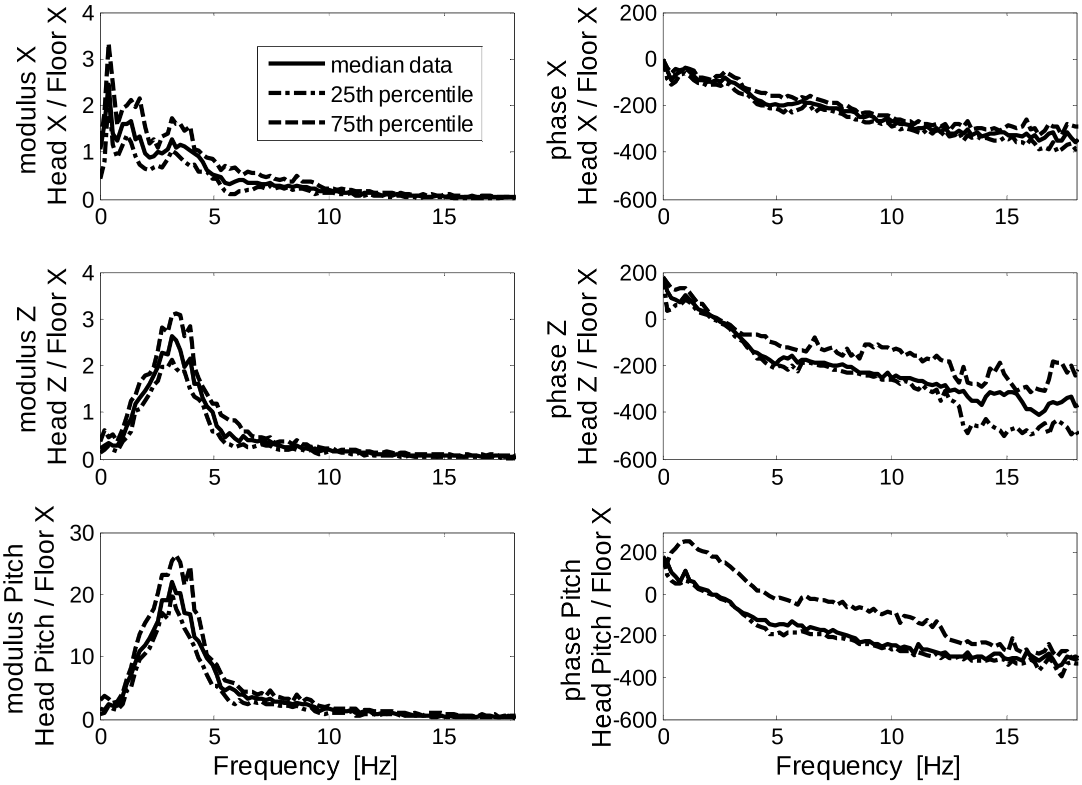


Figure 6.6 Floor-to-head transmissibility obtained with broadband random fore-and-aft excitation at 0.6 $m.s^{-2}$ r.m.s.

6.6 RESULTS

6.6.1 Floor-to-head transmissibility

6.6.1.1 Floor-to-head transmissibility with sinusoidal excitation

Figure 6.4 shows the floor-to-head transmissibility obtained with sinusoidal fore-and-aft excitations. The input excitation was localized at the vibrator platform. The output responses were measured with accelerometers mounted on a bite-bar. In Figure 6.4 and for the following figures presenting transmissibilities, the modulus in the fore-and-aft and in the vertical direction is in $[m.s^{-2}]/[m.s^{-2}]$, the modulus of the pitch motions is in $[rad.s^{-2}]/[m.s^{-2}]$. The phase of the transmissibility is in [deg]. The medians, 25^{th} and 75^{th} percentile of the moduli and phase of the fore-and-aft, vertical and pitch transmissibility obtained with the 12 subjects are plotted in Figure 6.4.

The transmissibilities show a resonance around 3.5 Hz. For low frequencies of excitation, accelerations at the vibrator platform and at the head seem to be in phase. As the

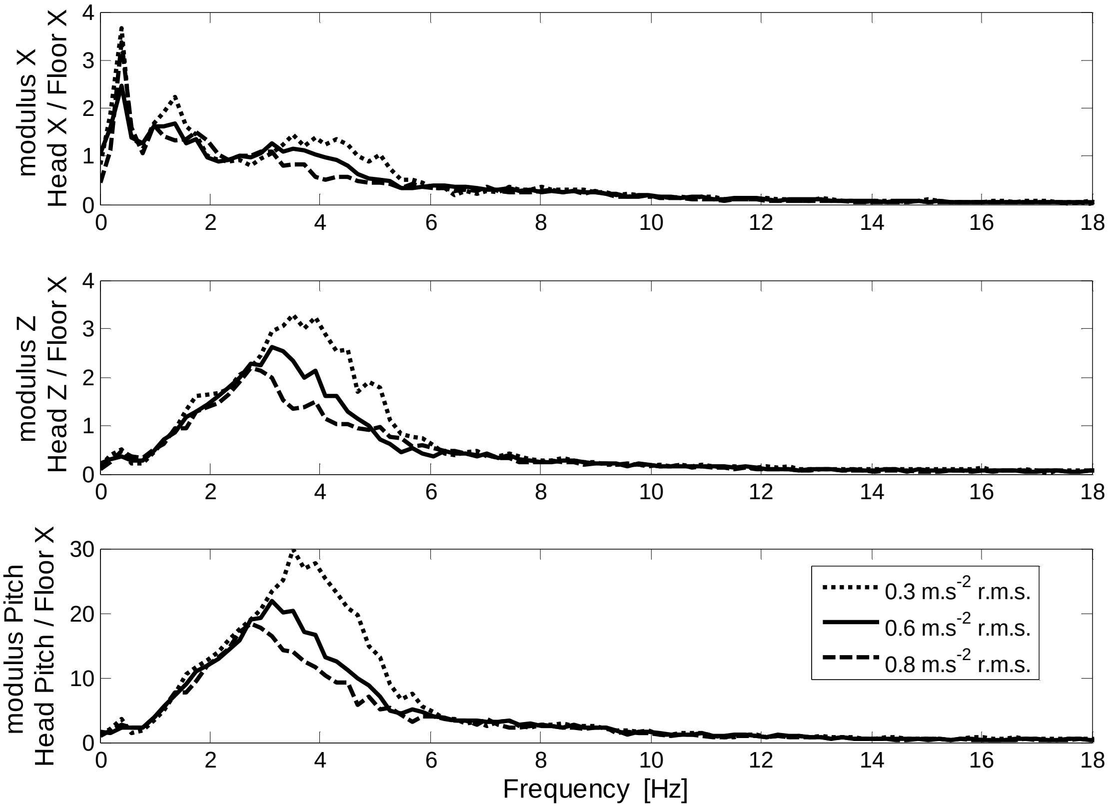


Figure 6.7 Effect of the magnitude of fore-and-aft broadband random excitation on the floor-to-head transmissibility.

frequency of excitation increases, the head response is delayed. At low frequencies (lower than 1 Hz), the modulus of the transmissibility should be interpreted carefully as the piezo-resistive measurements of the accelerometers are affected by a g.sin(θ) factor. The 25th and 75th percentiles represent inter-subject variability.

6.6.1.2 Floor-to-head transmissibility with narrow random excitation

Figure 6.5 shows the floor-to-head transmissibility obtained with narrowband random fore-and-aft excitation.

The transmissibilities show a resonance around 3.5 Hz. For low frequency excitation, accelerations at the vibrator platform and at the head seem to be in phase. As the frequency of excitation increases, the head response is delayed (as observed with the sinusoidal excitations). The inter-subject variability is low.

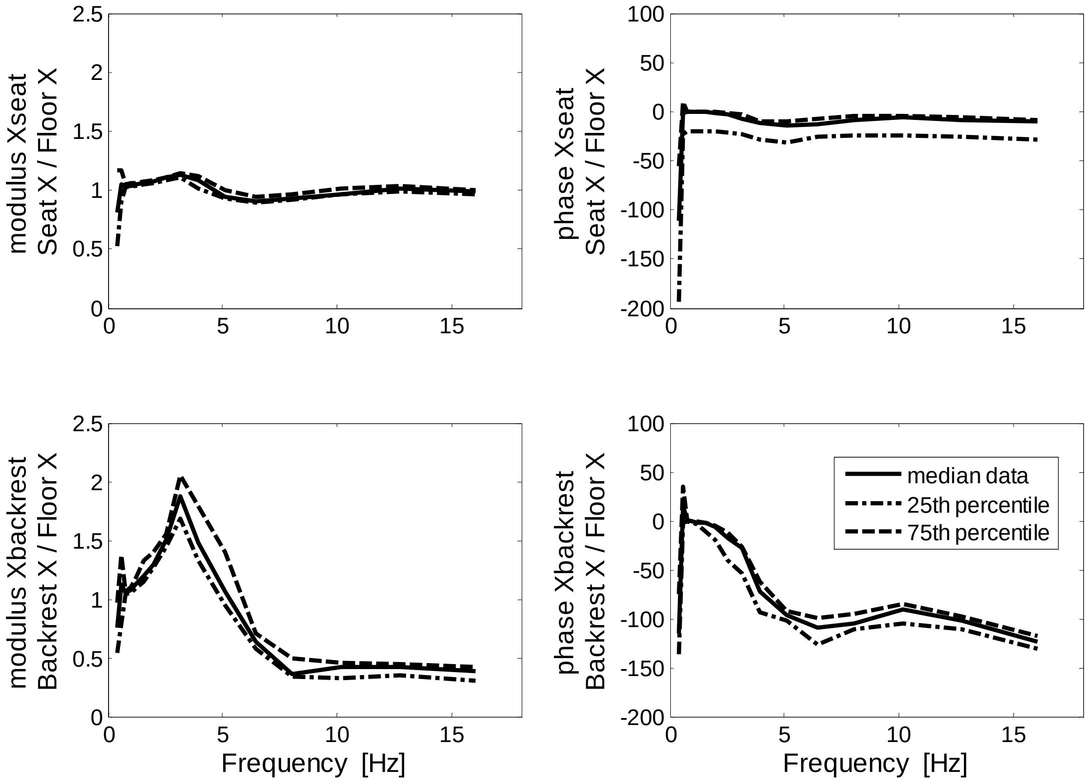


Figure 6.8 Seat-pan and backrest transmissibility measured with sinusoidal fore-and-aft excitation.

6.6.1.3 Floor-to-head transmissibility with broadband random excitation

Figure 6.6 shows the floor-to-head transmissibility obtained with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s.

The transmissibilities shown in Figure 6.6 were obtained with a continuous stimulus (whereas the transmissibilities shown in Figure 6.4 and 6.5 are composed of data points, each point was calculated from the exposure to one stimulus). Therefore the transmissibility measured with broadband random excitation has a better frequency resolution and is less affected by change of subject posture (that may happen between the presentation of two stimuli).

The transmissibilities show a resonance around 3.5 Hz for fore-and-aft, vertical and pitch motion of the head. Another resonance is observable around 1 Hz in the fore-and-aft transmissibility. At low frequencies, the piezo-resistive measurements of the accelerometers may be affected by a g.sin(θ) factor that affects the seat-to-head transmissibility.

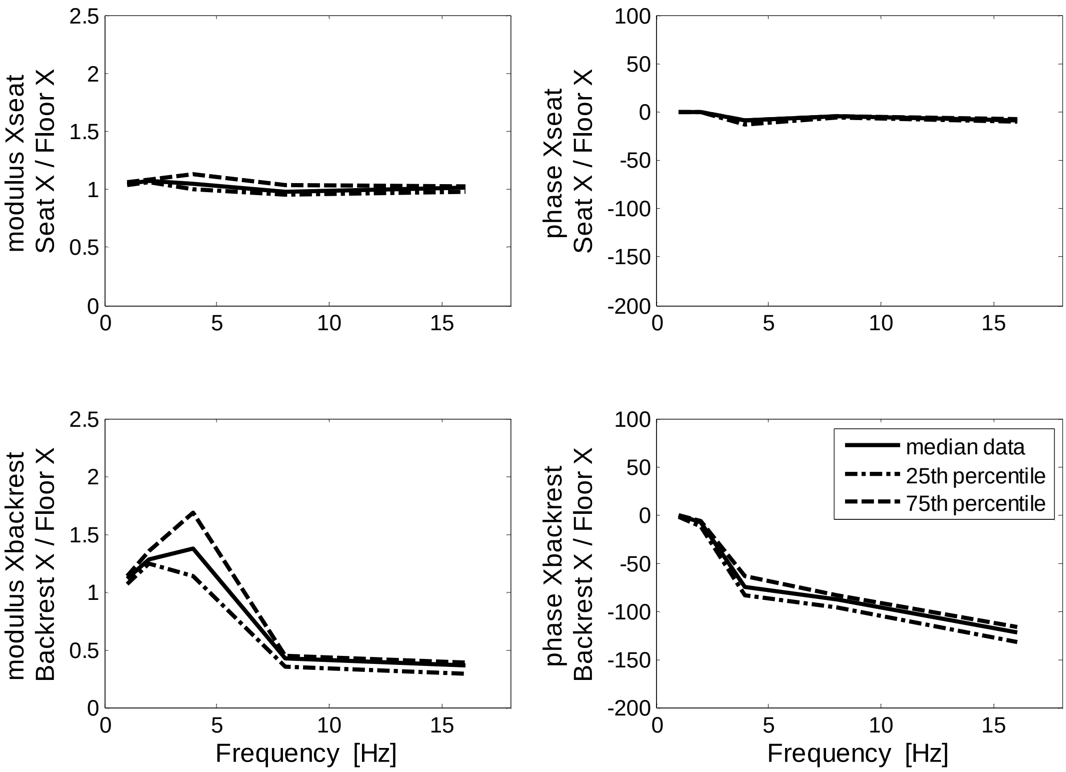


Figure 6.9 Seat-pan and backrest transmissibility measured with narrowband random fore-and-aft excitation.

Figure 6.7 shows the modulus of the floor-to-head and seat transmissibility obtained with fore-and-aft broadband random excitations at 0.3, 0.6 and 0.8 m.s^{-2} r.m.s. With increasing magnitude of excitation, the modulus and the frequency of the transmissibility at the resonance (around 1 Hz and 3.5 Hz) decrease.

6.6.2 Seat transmissibility

Figure 6.8, Figure 6.9 and 6.10 show the seat transmissibility measured with sinusoidal, narrowband random, and broadband random vibration at 0.6 m.s^{-2} r.m.s. The input excitation was localized at the vibrator platform. The output responses were measured with accelerometers mounted in a SIT-pad on the backrest and another SIT-pad mounted on the seat pan.

Transmissibilities measured with sinusoidal, narrowband random and broadband random excitation show similar results. The seat-pan does not affect significantly the transmission of vibration from the floor to the subject. In the fore-and-aft direction, the seat-pan can be

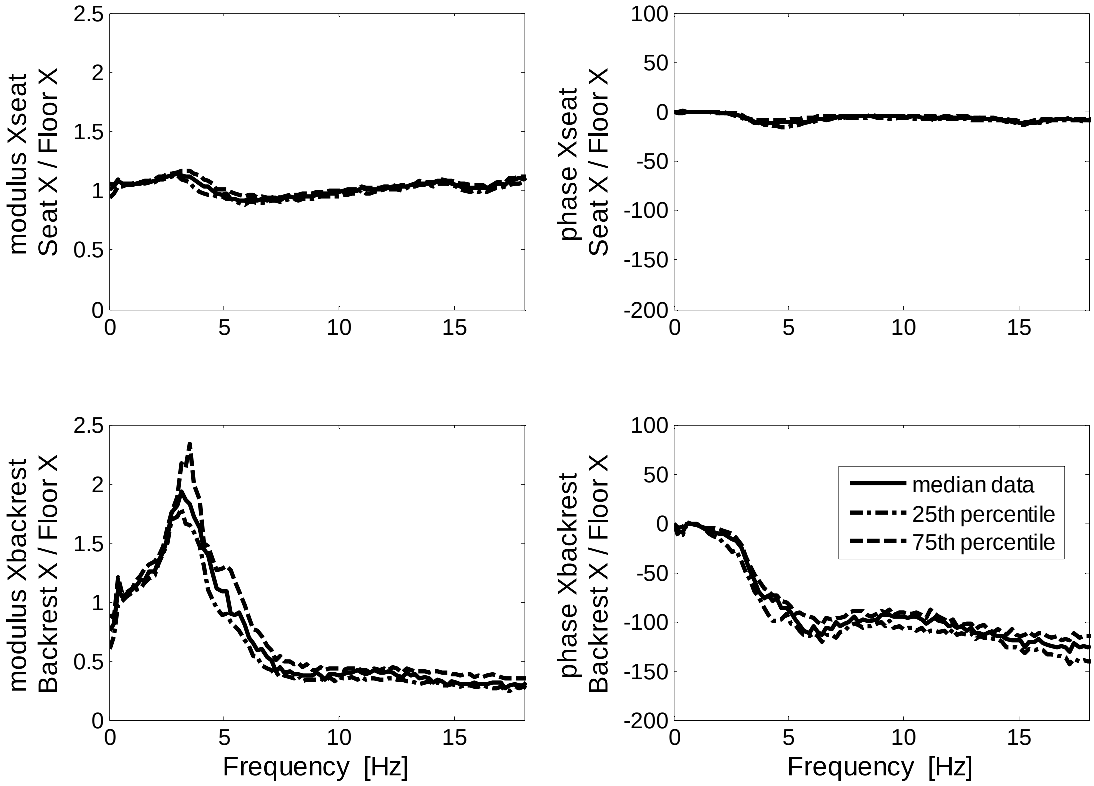


Figure 6.10 Seat-pan and backrest transmissibility measured with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s.

considered as rigid. However, the backrest affected greatly the transmission of the vibration by amplifying the vibration with a resonance around 3.5 Hz.

Figure 6.11 shows the modulus of the seat transmissibility obtained with fore-and-aft broadband random excitations at 0.3, 0.6 and 0.8 m.s^{-2} r.m.s. With increasing magnitude of excitation, the magnitude and the frequency of the transmissibility at the resonance (3.5 Hz) decreased. The same effect was observed for the floor-to-head transmissibility (see Figure 6.7). The seat transmissibility seems less affected by the magnitude of the excitation than the floor-to-head transmissibility. It could indicate that the seat by itself cannot explain the non-linearity observed in the floor-to-head transmissibility.

6.6.3 Seat-to-head transmissibility

Previous transmissibility results presented in this chapter were calculated using the vibrator platform as the input. Vibrations of the vibrator platform are transmitted to the seated body through the seat-pan and the backrest. Figure 6.12 shows the transmissibility calculated using the seat-pan and backrest inputs.

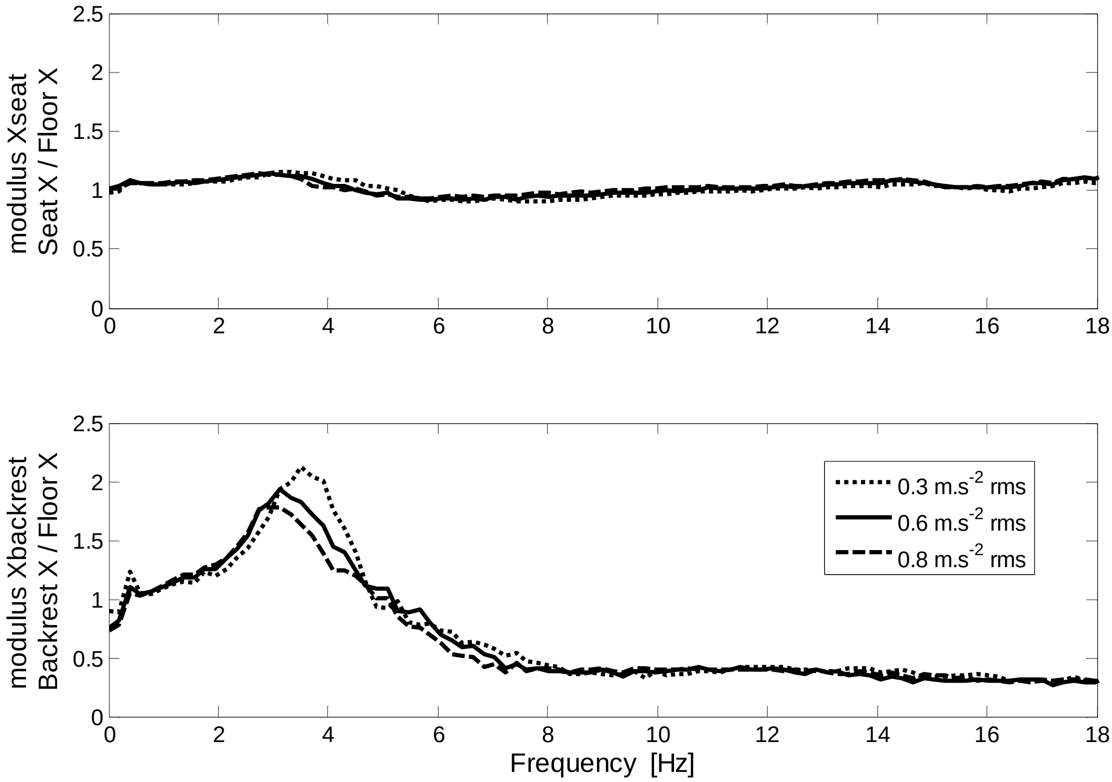


Figure 6.11 Effect of the magnitude of fore-and-aft broadband random excitation on the seat pan and backrest transmissibility.

Figure 6.12 shows that the seat-pan does not affect the transmission of the vibration from the vibrator platform to the head. This result was expected as the seat-pan transmissibility (presented in Figure 6.10) was close to unity. Great differences are observable between the floor-to-head transmissibility and the backrest-to-head transmissibility. This was expected as the backrest transmissibility amplifies the vibration around 3.5 Hz and reduces the transmission as the frequency increases (see Figure 6.10). The phase of the backrest-to-head transmissibility follows the same trends as the phase of the floor-to-head transmissibility. As the frequency increases, the phase difference between the two transmissibilities increases due to the damping of the car backrest.

6.7 DISCUSSION

6.7.1 Effects of the amplitude of the excitation on the transmissibility

The magnitudes of the sinusoidal and narrowband random excitations used in this study were identical to those used in the subjective and physiological studies (see Chapter 3 and

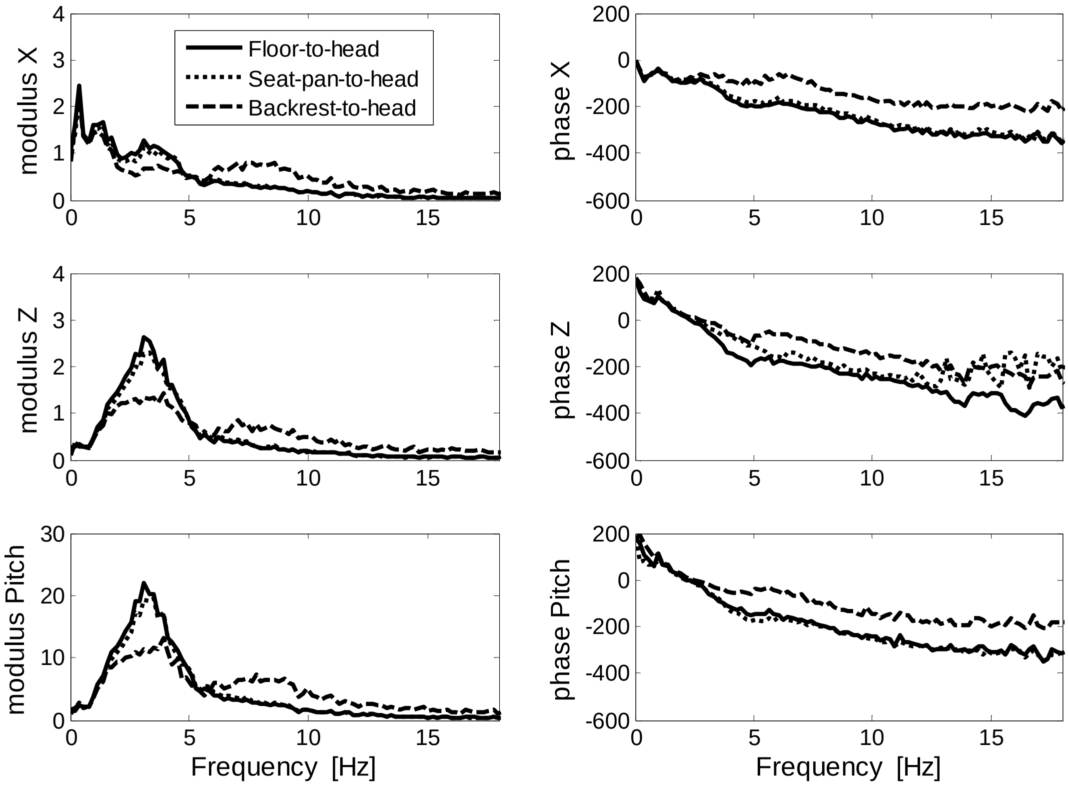


Figure 6.12 Effects of the input location on the transmissibility (obtained with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s.).

5). Different magnitudes were used at different frequencies: from 0.21 m.s^{-2} r.m.s. at 4 Hz to 1.10 m.s^{-2} r.m.s. at 16 Hz (see Table 6.1). Transmissibility was measured with broadband random excitation at three magnitudes to take in account the range of magnitudes used for sinusoidal and narrowband random excitation.

Figures 6.7 and 6.11 showed that the magnitude of excitation mainly affects the floor-to-head and seat transmissibilities around the resonance frequency. As the magnitude of the random fore-and-aft motion increased, the peak and the resonance frequency decreased.

This agrees with previous studies (Griffin *et al.*, 1979). With increasing excitation magnitudes it might seem reasonable to expect a stiffening of the response of the body and therefore an increase of the resonance frequency with increasing magnitude. However, transmissibility results and mechanical impedance of the body show a softening with increased vibration magnitude (Fairley and Griffin, 1989; Mansfield and Griffin, 2002).

The changes in the transmissibility due to vibration magnitude can be small compared with the differences that occur both within and between individual subjects (Griffin, 1990).

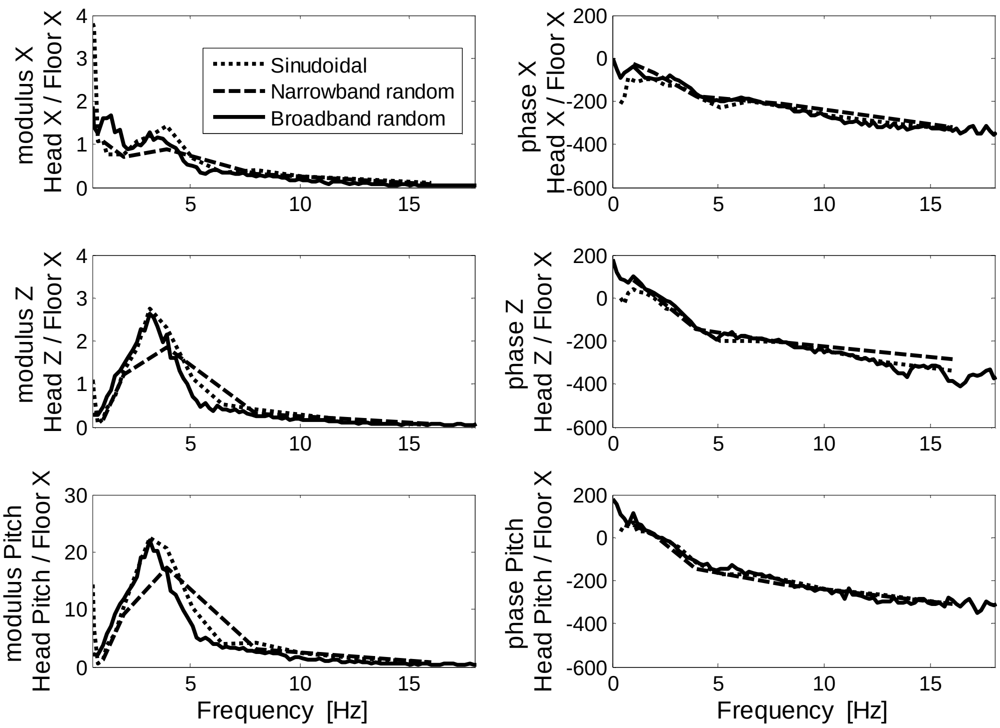


Figure 6.13 Effects of waveform of the excitation on the floor-to-head transmissibility (broadband random vibration used was at 0.6 m.s^{-2} r.m.s.).

Griffin *et al.* (1979) showed that back posture and head inclination have greater effects on seat-to-head transmissibility than does the magnitude of vibration. With increased magnitude, subjects can adopt (voluntarily or involuntarily) a posture than minimizes their discomfort, which may cause a non-linearity to be observed.

Floor-to-head transmissibility represents the response of the skeletal structure, whereas the mechanical impedance of the body is more dominated by the response of the body flesh (including muscles). Both transmissibility and impedance show non-linearity (Fairley and Griffin, 1989; Mansfield and Griffin, 2002). Therefore changes in the posture alone (which represents the motion of the skeletal structure) may not be the only reason for the non-linearity. Increased magnitude of excitation may also alter the type of response of the muscle by producing a loss of muscle tone and increased phasic muscle activity.

The resonance frequency of the seat transmissibility also decreased with increased vibration magnitude (see Figure 6.11). This result has also been reported in previous studies (Varterasian, 1981; Fairley and Griffin, 1986). Fairley (1983) showed that seat stiffness decreased with increasing the excitation magnitude, but this was not sufficient to account for the large changes observed in the resonance frequency.

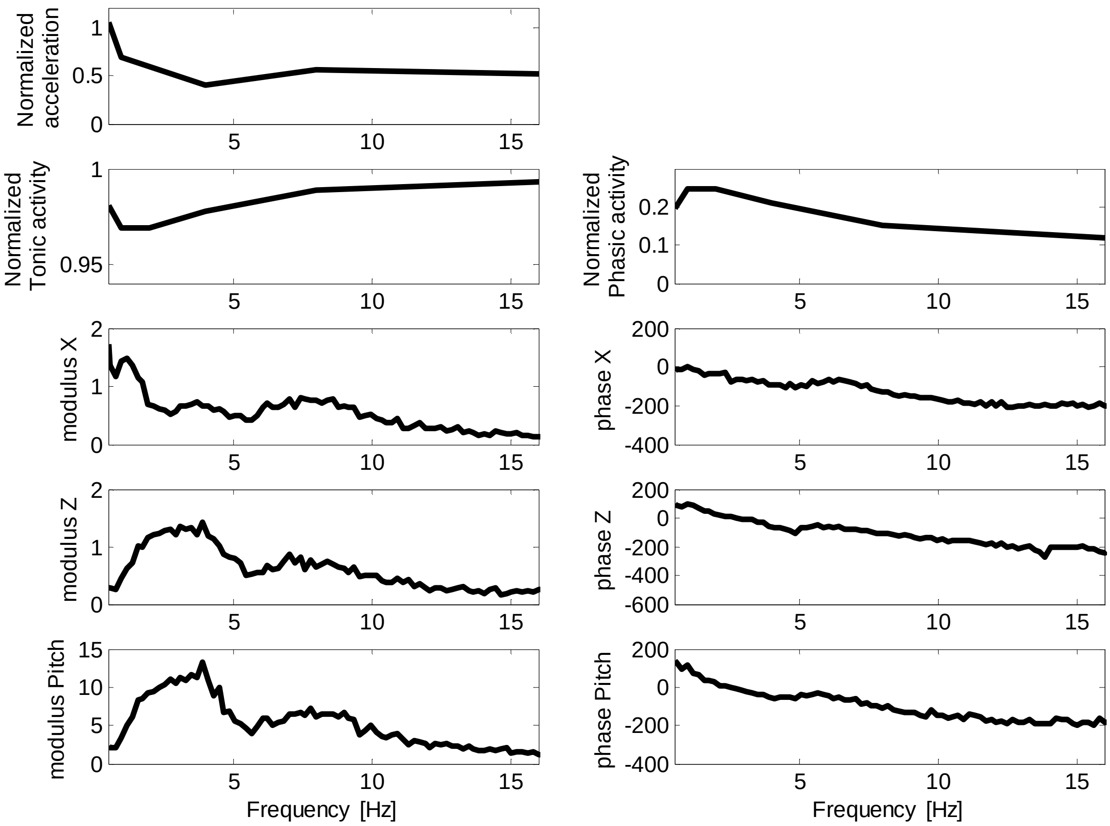


Figure 6.14 Relationship between SDTD (normalised acceleration), normalized phasic and tonic neck muscle activity and backrest-to-head transmissibility (0.6 $m.s^{-2}$ r.m.s.).

The non-linearity measured may have multiple causes. It is unclear from the present results which are the more critical.

6.7.2 Effects of the waveform of the excitation on the transmissibility

Figure 6.13 shows the effect of the waveform of the excitation on the seat-to-head transmissibility. The moduli and phases of the floor-to-head transmissibilities seem to be not greatly affected by the waveform of the excitation. Most of the differences observed in the transmissibility results may be due to the frequency resolution.

For the fore-and-aft direction (modulus X in Figure 6.13), at frequencies less than 1 Hz, sinusoidal and broadband random excitation seems to produce a different transmissibility. At low frequencies (less than 1 Hz), the modulus of the transmissibility should be interpreted cautiously as the piezo-resistive measurements of the accelerometers are affected by a g.sin(θ) factor.

The construction of the transmissibility curves measured with sinusoidal and narrowband random excitations required exposure to stimuli at different frequencies. Between stimuli, the posture of the subjects might have changed and altered the transmissibility. Considering this potential cause of variability, the results showed similar transmissibilities between the different waveforms of excitation.

Subjective discomfort time-dependency (SDTD) was not affected by the waveform of the excitation (see Chapter 3). If, as hypothesised, SDTD can be predicted depending on the type of head motions, sinusoidal and narrowband random excitation should produce similar floor-to-head transmissibility.

6.7.3 Relationship between head motion, neck muscle activity and subjective discomfort time-dependency (SDTD)

6.7.3.1 Introduction

Figure 6.14 presents the median normalized acceleration showing the SDTD measured for fore-and-aft excitation (top graph), the normalized tonic and phasic neck muscle activities, and the modulus and phase of the backrest-to-head transmissibility measured with a broadband random excitation at 0.6 $m.s^{-2}$ r.m.s. The backrest-to-head transmissibility represents head motions relative to the upper-back. Backrest-to-head transmissibility is more suitable than the floor-to-head transmissibility for predicting SDTD.

The normalized acceleration curve was built from the SDTD data presented in Chapter 3. For 0.5 Hz, the sinusoidal normalized acceleration was taken at the 15th minute of exposure; for 1, 4, 8 and 16 Hz, the narrowband random normalized accelerations were taken at the 30th minute of exposure. The normalized acceleration curve presented in Figure 6.14 is similar to a comfort contour curve measured after 30 minutes of exposure (from 1 Hz to 16 Hz). This means that lower magnitudes of the normalized acceleration curve represent motions that produced greater SDTD.

The normalized tonic and phasic neck muscle activities presented in Figure 6.14 were obtained in Chapter 5 (Section 5.6.2). It was suggested that SDTD may be proportional to the ratio of the phasic neck muscle activity to the tonic neck muscle activity. It was also discussed that the magnitude of the absolute tonic activity produced by different frequencies of excitation could also play a role in the discomfort time-dependency (see Chapter 5, Section 5.7.5). It was suggested that:

- Phasic activity represents a periodic contraction of the neck muscle fibres. This type of neck muscle activity may result in a periodic head motion. Phasic muscle activity implies that the muscle fibres are not exerting a constant tension. This appears to result in only a low SDTD.

- Tonic activity represents a state where the neck muscle fibres are contracted ‘continuously’. Greater tonic activity may imply that the neck muscles tend to reduce the head motions. Tonic muscle activity implies that the muscle fibres are exerting a constant tension and this appears to result in a high SDTD.

6.7.3.2 Relationship between the normalized phasic neck muscle activity and the phase of the backrest-to-head transmissibility.

Figure 6.14 shows that head motions are in phase (in the fore-and-aft direction) or even lead (for the pitch and vertical direction) the vibrator platform acceleration at frequencies less than about 2 Hz. As the frequency of excitation increases above 2 Hz, there is an increasing phase lag between the head motions and the platform acceleration. Normalized phasic activity follows the same trend. Normalized phasic activity is greater at low frequencies. Then as the frequency increases above 2 Hz, the normalized phasic activity decreases. Similar results, from Robertson and Griffin (1989), have been obtained with studies investigating back muscle activity during exposure to fore-and-aft excitation. They found that muscle activity led, or was in phase with, the platform acceleration up to 2 Hz. At higher frequencies, the EMG showed an increasing lag behind the acceleration (see Figure 5.8 in Chapter 5).

From Figure 6.14, it seems that changes in the phase of the backrest-to-head transmissibility correspond to changes in the normalized phasic activity. One further step in understanding the relationship between the phase of the backrest-to-head transmissibility and the phasic activity could be reached by considering the ‘dynamic’ properties of the muscle fibres. The phase of the seat-to-head transmissibility at low frequencies may be influenced by, or influences, the phasic muscle activity, which depends on the ‘dynamic’ properties of the muscle fibres. From this study and the previous studies presented in Chapter 5 and discussed in Section 5.7.3 (Freund, 1983; Seidel *et al.,* 1986; Seidel, 1988; Robertson and Griffin 1989), the muscle fibres seem to respond in phase with excitation at frequencies below about 2 Hz. As the frequency increases, the ability of the muscles fibres to respond to the excitation reduces. These properties may explain the phasic activity and therefore the phase of the backrest-to-head transmissibility.

6.7.3.3 Relationship between the tonic neck muscle activity and the modulus of the backrest-to-head transmissibility

As presented in Chapter 5, Section 5.2.3.5, muscle activity during exposure to vibration is assumed to be composed of phasic and tonic activity. Because the normalisation of the phasic and tonic activity was performed relative to the total neck muscle activity, the normalized tonic activity is inversely proportional to the normalised phasic activity (see Chapter 5, Section 5.6.2).

It has been shown in Section 6.7.4.2 that the normalized phasic activity varies with the frequency of vibration similarly to the phase of the backrest-to-head transmissibility. The normalized tonic activity therefore also varies with the phase of the backrest-to-head transmissibility.

Figure 6.14 allows comparison between the normalized tonic activity and the modulus of the backrest-to-head transmissibility. The modulus presents four characteristics: a resonance in the fore-and-aft direction around 1 Hz, a second vertical and pitch resonance around 3.5 Hz, a third fore-and-aft, vertical and pitch resonance around 7 Hz and reduced motion of the head relative to the upper-back as the frequency increases. These four characteristics present three different combinations of phasic and tonic activity:

- Around 1 Hz, the head motions are controlled by the phasic activity. So it is suggested that the resonance will not affect the absolute magnitude of the tonic muscle activity but it will affect the absolute magnitude of the phasic muscle activity.
- Around 3.5 Hz and 7 Hz, the head motions are controlled by both phasic and tonic activity. It is suggested that the magnitude of the peak head motion will affect the absolute magnitude of both the tonic and the phasic muscle activity.
- At frequencies greater than 10 Hz, the head motions are increasingly controlled by the tonic muscle activity. Tonic neck muscle activity tends to reduce the head motion caused by the whole-body exposure to vibration. Greater magnitudes of head motion caused by vibration will probably require more tonic activity. The magnitude of the head motion in this frequency range may directly affect the magnitude of the tonic muscle activity.

6.7.3.4 Relationship between the seat-to-head transmissibility and subjective discomfort time-dependency

Figure 6.14 shows there is no direct relationship between subjective discomfort time dependency (SDTD) and either the phase or the modulus of the backrest-to-head transmissibility. Any relation between SDTD and backrest-to-head transmissibility exist only through the activity of the neck muscles.

From the Sections 6.7.3.2 and 6.7.3.3, and the results of Chapter 5, Section 5.7.5, it is suggested that the ratio of the phasic activity to the tonic activity and the magnitude of the tonic activity may be estimated from the backrest-to-head transmissibility. This estimation assumes that the backrest-to-head transmissibility reflects head motions involving the neck muscles. Being aware of this assumption, SDTD may be estimated from the backrest-to-head transmissibility in two main steps.

Step 1:

For the frequency range investigated, three continuous 'zones' could be determined. The first zone includes the frequencies for which head motions are mainly controlled by phasic muscle activity. The second zone includes the frequencies for which head motions are controlled by both phasic and tonic muscle activity. A third zone includes the frequencies for which the head motions are controlled mainly by tonic muscle activity. These three zones can be identified from the phase of the backrest-to-head transmissibility:

- The frequency boundary between the first and second zone may be defined by the frequency at which the head motion begins to present a phase lag relative to the upper-back. This zone can be considered to cause a low discomfort time-dependency.
- The boundary between the second and third zone is more difficult to determine. Results presented in Chapter 5 show that as the frequency increases, the normalized tonic activity increases and the normalized phasic activity decreases (see Chapter 5, Section 5.6.2). Previous studies (Freund, 1983; Seidel *et al.,* 1986; Seidel, 1988) suggested that at frequencies greater than 16 Hz the muscle fibres are no longer able to produce phasic activity and therefore head motions at such higher frequencies would be controlled entirely by tonic activity. The second zone may be considered as causing an intermediate discomfort time-dependency (because some muscle fibres can relax during a cycle), and the third zone as causing a greater discomfort time-dependency (because all muscle fibres will be contracted continuously).

Step 2:

The modulus of the backrest-to-head transmissibility may represent the magnitude of the head motion relative to the upper-back if the input acceleration at the upper-back is known. Depending on the zone, the modulus of the backrest-to-head transmissibility may affect SDTD in different ways:

- A resonance in the first zone would not cause a great discomfort time-dependency as the head motions are controlled by phasic activity which is associated with low SDTD.
- A resonance in the second zone will be more critical for SDTD. Head motions in the second zone are expected to produce tonic activity: a resonance in the backrest-to-head transmissibility will increase the amount of tonic activity required to control the head motion, and the increased tonic muscle activity will gradually produce greater SDTD.
- The third zone presents the highest discomfort time-dependency because head motions are controlled mainly by tonic activity. A resonance of the backrest-to-head transmissibility will be critical for SDTD as there will be more tonic muscle activity produced in an effort to control head motion. This condition would be expected to produce the greatest discomfort time-dependency..

6.7.3.5 Conclusion

Assuming that the backrest-to-head transmissibility represents the head and neck motions relative to the upper-back and that the input acceleration at the upper-back is known, subjective discomfort time-dependency may be estimated from the phase and modulus of the backrest-to-head transmissibility. The next section will investigate how floor-to-head transmissibility can be predicted and how the corresponding backrest-to-head transmissibility may be estimated.

6.7.4 Prediction of the floor-to-head transmissibility and the corresponding backrest-to-head transmissibility

6.7.4.1 Introduction

From engineering point of view it is interesting to predict head motions and the subjective discomfort time-dependency (SDTD) from the vibration at the floor and the dynamic properties of the car seat. Input vibration and dynamic properties of the seat might be ‘tuned’ so that less discomfort is generated with duration. Floor-to-head transmissibility and seat transmissibility were measured to investigate whether the floor-to-head transmissibility could be estimated from the seat-to-head transmissibility measured on a rigid seat and the known properties of the car seat.

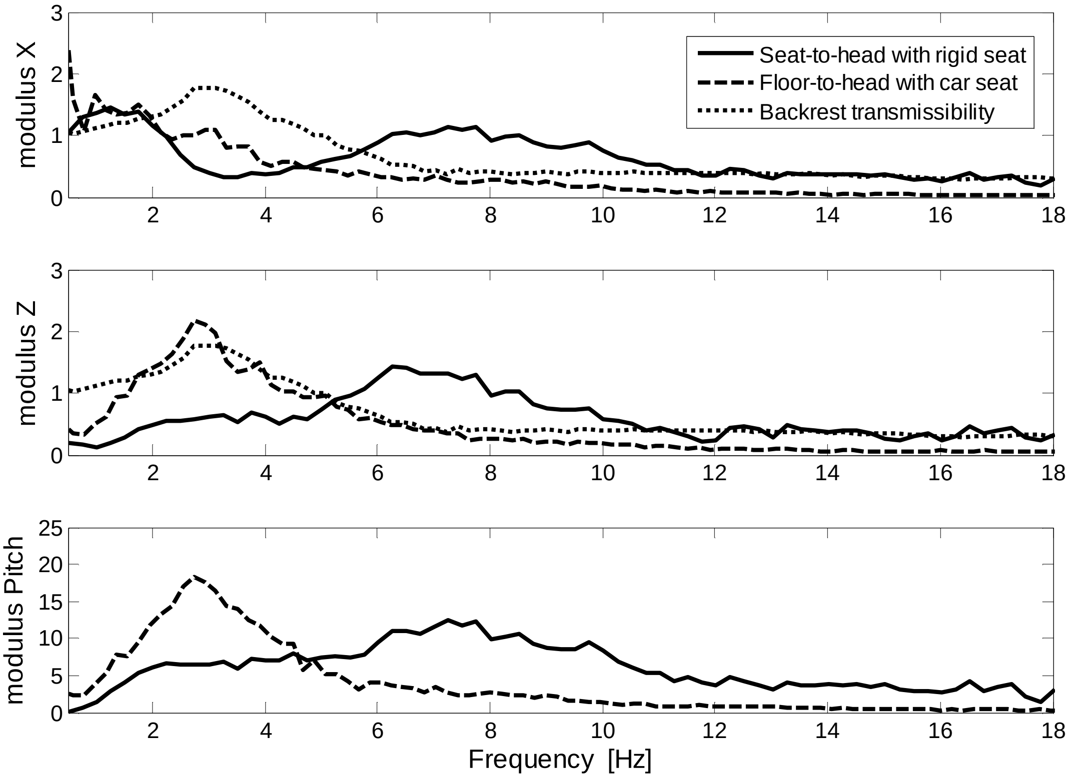


Figure 6.15 Effect of the car seat dynamic properties on the head motions (_ : Seat-to-head transmissibility data obtained by Paddan and Griffin, 1996, with broadband random fore-and-aft excitation at 1.75 m.s^{-2} r.m.s.; -- :Floor-to-head transmissibility obtained with broadband random fore-and-aft excitation at 0.8 m.s^{-2} r.m.s.; .. : Backrest transmissibility measured simultaneously with the floor-to-head transmissibility showed).

Floor-to-head transmissibility cannot be used directly to predict SDTD as the head motions are related to the platform acceleration and not necessarily representative of the involvement of the neck muscles. Backrest-to-head transmissibility seems to be more suitable than the floor-to-head transmissibility to represent the head and neck motions relative to the upper-body. The second part of this section will investigate the possible means to estimate the backrest-to-head transmissibility from the floor-to-head transmissibility and the known dynamic properties of the backrest.

6.7.4.2 Predicting the floor-to-head transmissibility from the seat-to-head transmissibility measured on a rigid seat and the backrest transmissibility

Figures 6.10 and 6.12 show the effects of the seat dynamic properties on the floor-to-head transmissibility. The seat-pan can be considered as almost rigid for fore-and-aft excitations as it does not attenuate or amplify vibrations transmitted to the seated body. However, as

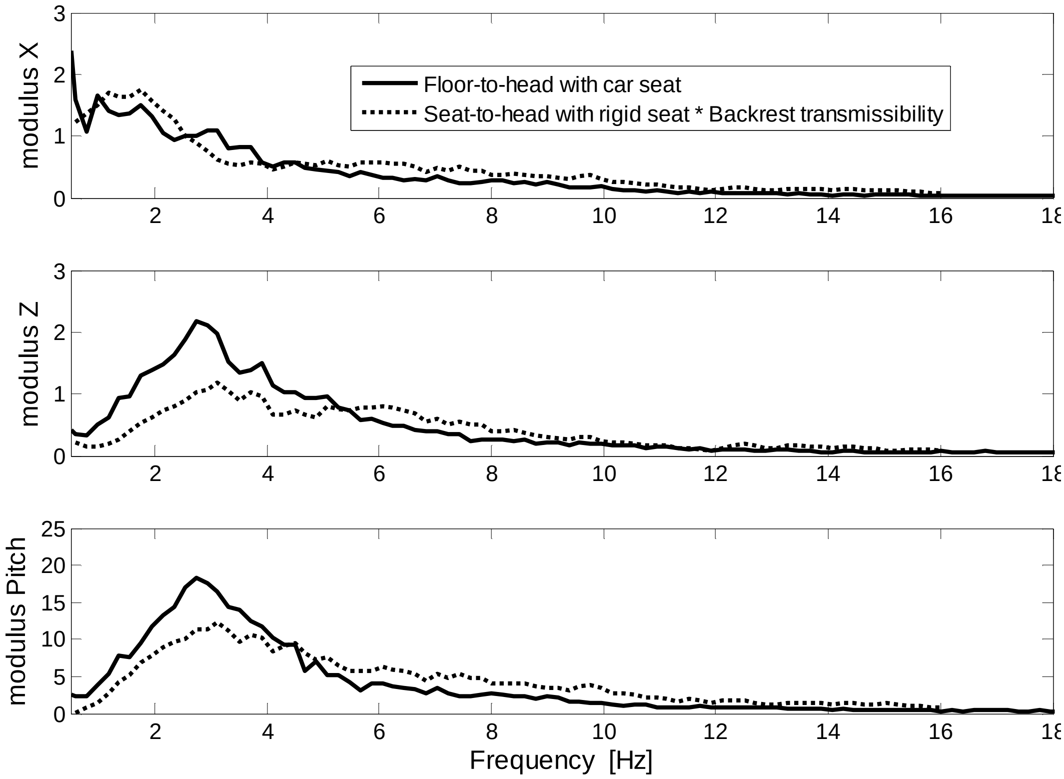


Figure 6.16 Effect of the car seat dynamic properties on the head motions (_ : Floor-to-head transmissibility measured with broadband random fore-and-aft excitation at 0.8 m.s^{-2} r.m.s.; **..** : Seat-to-head transmissibility obtained from Paddan and Griffin, 1996, measured on a rigid seat with broadband random fore-and-aft excitation at 1.75 m.s^{-2} r.m.s. multiplied by the backrest transmissibility measured simultaneously with the floor-to-head transmissibility showed).

hypothesised, the backrest affects greatly the transmission of the vibration with amplification around 3.5 Hz and increased attenuation as the frequency increases.

Figures 6.15 and 6.16 present the effects of the backrest dynamic properties on the floor-to-head transmissibility measured on a car seat compared to seat-to-head transmissibility measured on a rigid seat. Figure 6.15 shows how the transmissibility measured with a car seat can be predicted according to transmissibility measured on a rigid seat and the backrest transmissibility. Figure 6.16 represents the transmissibility measured on a rigid seat multiplied by the backrest transmissibility. This curve is compared with the transmissibility measured on a car seat.

The seat-to-head transmissibility used in figures 6.14 and 6.15 was measured by Paddan and Griffin (1996) with a subject seated on a rigid seat and exposed to fore-and-aft broadband random vibration at 1.75 m.s^{-2} r.m.s. The floor-to-head and backrest

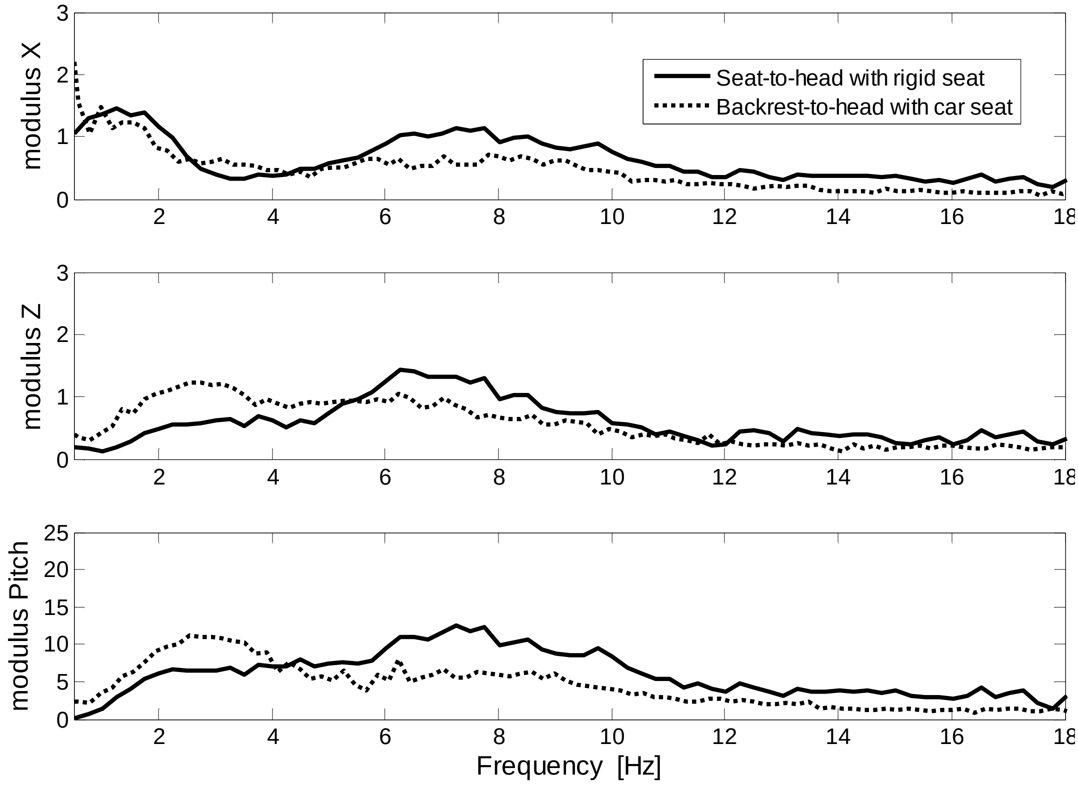


Figure 6.17 Effect of the car seat dynamic properties on the head motions (_ : Seat-to-head transmissibility obtained from Paddan and Griffin, 1996, measured on a rigid seat with broadband random fore-and-aft excitation at 1.75 m.s^{-2} r.m.s.; **..** : Backrest-to-head transmissibility measured on a car seat with broadband random fore-and-aft excitation at 0.8 m.s^{-2} r.m.s.).

transmissibility were obtained with a car seat with broadband random vibration at 0.8 m.s^{-2} r.m.s. Many parameters may affect the quality of the prediction. The seat-to-head transmissibility taken from the Paddan and Griffin (1996) studies was from one subject, whereas the floor-to-head and backrest transmissibilities used for comparison are the median transmissibilities of 12 subjects. Because a different seat was used, subjects may have adopted different postures. Also the excitation magnitude used for the rigid seat study was more than twice the excitation magnitude used in this study.

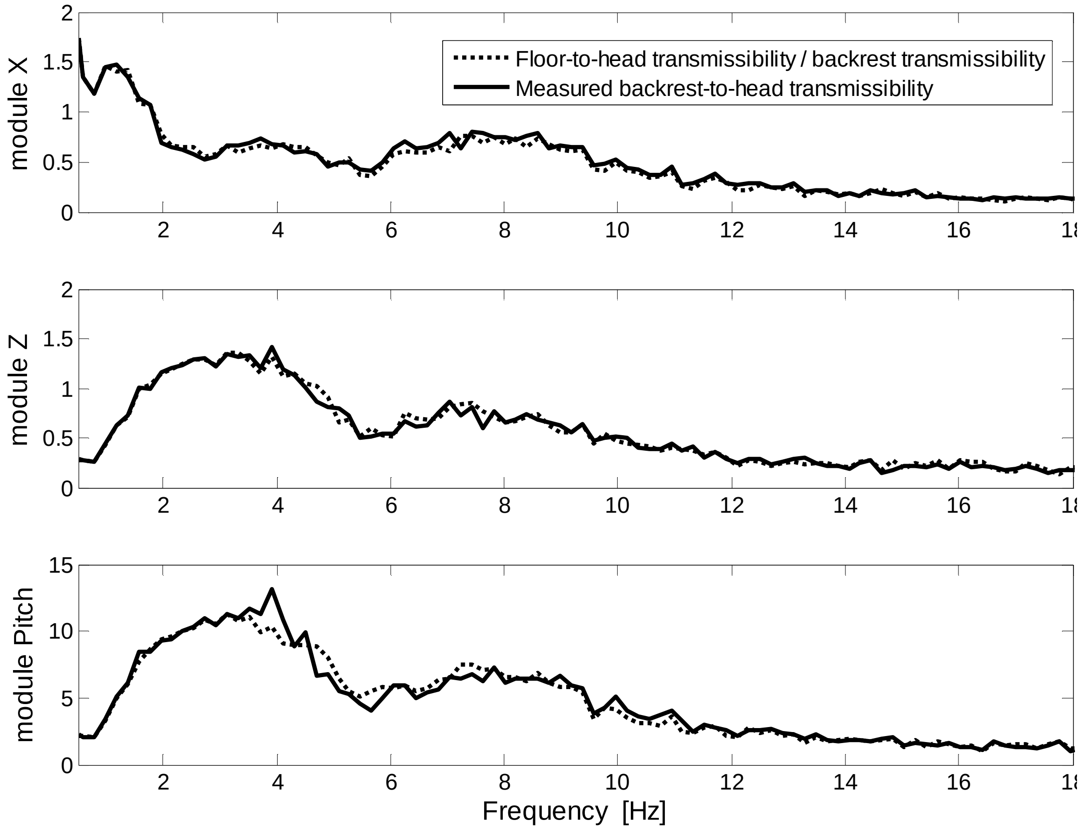


Figure 6.18 Effect of the car seat dynamic properties on the head motions (_ : Measured backrest-to-head transmissibility on a car seat with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s. at the platform; **..** : floor-to-head transmissibility measured on a car seat with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s. divided by the measured backrest transmissibility measured in the fore-and-aft direction).

Realising that the frequency and magnitude of the resonance decreases with increasing excitation magnitude, it seems that floor-to-head transmissibility measured on a car seat can be reasonably well predicted from the backrest transmissibility and the seat-to-head transmissibility measured on a rigid seat. Therefore motions at the head can be predicted from the dynamic properties of the backrest and knowledge of the seat-to-head transmissibility measured on a rigid seat.

6.7.4.3 Predicting the backrest-to-head transmissibility from the floor-to-head transmissibility and the known backrest transmissibility.

Figure 6.16 shows how the floor-to-head transmissibility measured on a car seat may be predicted from the car backrest transmissibility and the seat-to-head transmissibility measured on a rigid seat. Taking as the input of the transfer function the acceleration between the backrest and the subject should isolate the seat dynamic properties. Therefore, the transmissibility calculated between the backrest and the head should be equivalent to the seat-to-head transmissibility measured on a rigid seat.

Figure 6.17 shows the comparison between the transmissibility measured on a rigid seat and the backrest-to-head transmissibility measured on a car seat. The Figure shows that even if there are some similarities between backrest-to-head transmissibility and the seat-to-head transmissibility measured on a rigid seat by Paddan and Griffin (1996), the curves still present differences. There are various reasons that may explain the differences:

- The backrest acceleration taken as input is very different from the flat broadband random excitation generated by the vibrator platform. Therefore the non-linearity of the body observed may explain some of the differences.
- Studies have shown that with fore-and-aft excitation, the backrest may also transmit vibrations in the vertical direction (Fairley, 1984; Nawayseh and Griffin, 2005). Therefore taking only the response of the backrest in the fore-and-aft direction does not represent totally the dynamic behaviour of the seat.
- The backrest and the back of the subject are interacting. Therefore the backrest acceleration, even with a rigid seat, would be different from the acceleration measured at the vibrator platform or at the seat-pan.

It seems that using the estimated floor-to-head transmissibility (obtained by the seat-to-head transmissibility measured on a rigid seat multiplied by the backrest transmissibility) provides a very rough estimation of the backrest-to-head transmissibility. The prediction of subjective discomfort time-dependency will require an accurate prediction of the head and neck motions relative to the upper-body.

Backrest-to-head transmissibility can be predicted from the measured floor-to-head transmissibility divided by the measured backrest transmissibility. Figure 6.18 compares the measured backrest-to-head transmissibility with the floor-to-head transmissibility divided by the backrest transmissibility. The figure shows that the backrest-to-head transmissibility can be well predicted if the floor-to-head transmissibility is accurate.

6.7.4.4 Conclusion

Figure 6.16 shows that floor-to-head transmissibility can be reasonably well estimated from the product of the seat-to-head transmissibility (with a rigid seat) with the backrest transmissibility. This is advantageous for engineers because floor-to-head transmissibility can be estimated for any seat if the backrest dynamic properties are known. It also requires no dynamic model. However Figure 6.17 showed that the corresponding estimated backrest-to-head transmissibility provides a very rough estimation of the measured backrest-to-head transmissibility. As subjective discomfort time-dependency (SDTD) may be estimated from head and neck motions relative to the upper-body (through neck muscle activity), a poor prediction of the backrest-to-head transmissibility will provide a poor prediction of the SDTD.

Figure 6.18 showed that the backrest-to-head transmissibility may be well predicted if the floor-to-head transmissibility is accurate. This suggests that a dynamic model predicting an accurate floor-to-head transmissibility is required. Chapter 7 presents a dynamic model predicting the floor-to-head transmissibility and the corresponding backrest-to-head transmissibility.

6.8 CONCLUSION

This study of the transmission of vibration from the floor to the seat, from the floor to the head, and from the seat to the head, suggests that subjective discomfort time-dependency (SDTD) may be estimated from the backrest-to-head transmissibility (assumed to represent the head and neck motions relative to the upper-back), through the neck muscle activity.

Predictions of the backrest-to-head transmissibility may be used to estimate SDTD. It was suggested that the backrest-to-head transmissibility may be accurately predicted by the floor-to-head transmissibility and the backrest transmissibility (which is more interesting for engineering purposes as it includes both the vibration input at the floor and the dynamic properties of the seat) only if the floor-to-head transmissibility is accurate. Chapter 7 investigates further these results and presents a biodynamic model capable of predicting the floor-to-head transmissibility and the corresponding mode shapes and the backrest-to-head transmissibility.

7 HEAD-NECK MODEL

7.1 INTRODUCTION

Subjective studies (Chapter 3) found that different frequencies of excitation produce different subjective discomfort time-dependencies (SDTD). They also showed that dynamic discomfort was mainly localized at the neck. Physiological studies (Chapter 5) found that discomfort increased at a faster rate with motions producing higher tonic activity and lower phasic activity. It was also suggested that magnitude of the tonic activity may estimate the SDTD. Chapter 7 showed that the phase of the backrest-to-head transmissibility followed the same trends as the normalized phasic neck muscle activity (over the frequency range investigated). It was then suggested that SDTD may be estimated from the modulus of the backrest-to-head transmissibility (if the input vibration at the backrest is known) depending on the phasic / tonic muscle activity ratio. It was concluded that a biodynamic model of the head and neck response may be able to estimate the SDTD.

This chapter presents a three degree-of-freedom lumped parameter model composed of three masses (nominally the head, the neck and the upper back), three springs and dampers. This type of model allows, through the calculation of the mode shapes (eigen values and eigen vectors) the determination of the resonance frequencies and the motion of the masses relative to each other. Using the mode shapes of this model, the head motions expected to produce the discomfort time-dependency may be identified. The model was developed to predict the floor-to-head transmissibility and the corresponding backrest-to-head transmissibility (from the known backrest transmissibility).

A main limitation of the model that has been developed is that the parameters have been adjusted from floor-to-head transmissibility data measured on one specific car seat. The model will probably not be optimum for another seat. Different means were tried to predict the floor-to-head transmissibility from the known dynamic properties of the seat. One possible solution was investigated in Chapter 6. It was shown that the floor-to-head transmissibility can be reasonably well predicted from the product of the known seat-to-head transmissibility measured with a rigid seat and the backrest transmissibility. However, with this solution, the resulting backrest-to-head transmissibility was not very accurate. This study presents a second solution, which suggests that the floor-to-head transmissibility can be predicted for any seat by injecting in the model the dynamic stiffness and damping of the backrest.

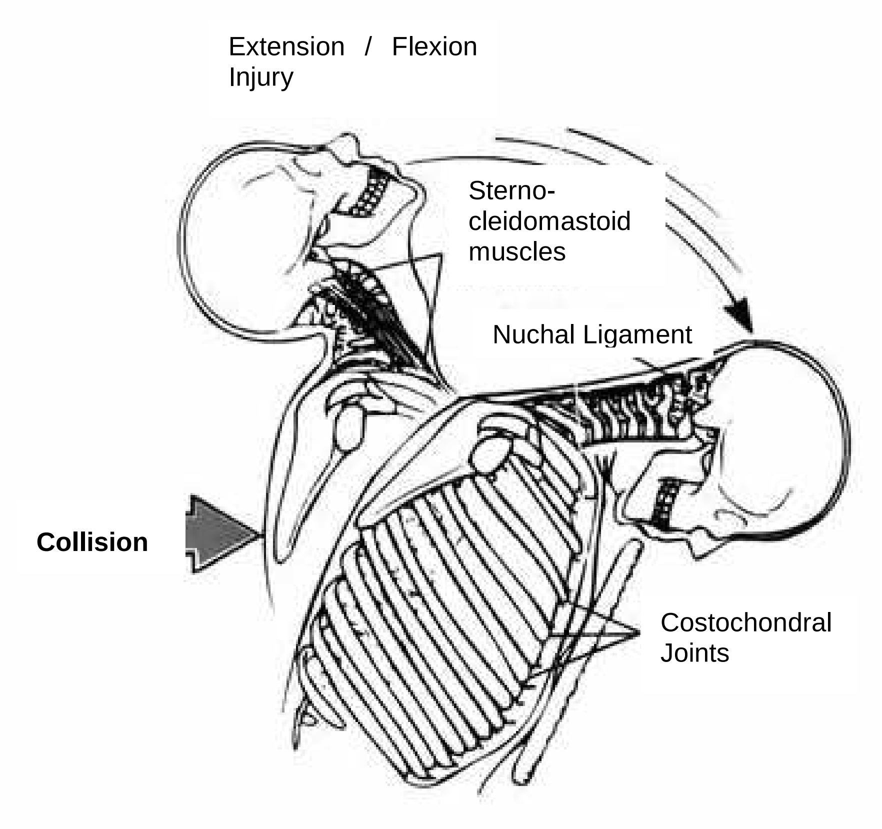


Figure 7.1 Example of a whiplash motion.

This chapter starts by describing various head-neck models available in the recent literature. The second part of the chapter consists of developing and optimising a three degree-of-freedom lumped parameter model of the dynamic response of the head and neck to fore-and-aft excitation. The parameters of this model were optimised using data obtained with a subject seated on a rigid seat (data from Paddan and Griffin, 1988). The model was then used to predict the floor-to-head transmissibility and the corresponding backrest-to-head transmissibility obtained in Chapter 7. A method to predict the floor-to-head transmissibility from the dynamic properties (dynamic stiffness and damping) was suggested.

7.2 BIODYNAMIC HEAD-NECK MODELS IN THE LITERATURE

7.2.1 Whiplash models

During the last 30 years, numerous head-neck models have been developed, largely in response to head-neck injuries in automobile accidents. These injuries consist of hyperextension or whiplash of the head-neck system caused by short duration high magnitude acceleration. Figure 7.1 shows an example of a whiplash motion. The models tend to predict the response of the head-neck complex to force or acceleration applied to

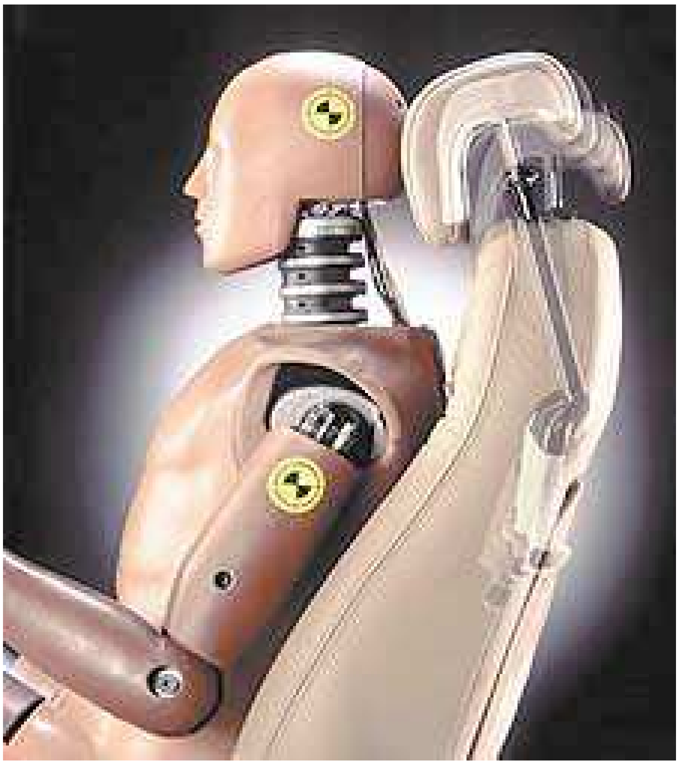


Figure 7.2 Photo of the Hybrid III test dummy.

the neck, generally fore-and-aft impulsive excitation localised at the thoracic vertebrae, T1. The models vary from one or two degree-of-freedom systems to multi-body systems (e.g., Tarriere and Sapin, 1968; Becker, 1973; King and Mertz, 1973; Frisch *et al.*, 1977; Reber and Goldsmith, 1979; William and Belytschko, 1981). Numerical models such as HUMOS (Robin, 2001) have been developed before expensive prototype dummies are built. The most commonly used test dummy for predicting injury in crash testing is the Hybrid III developed by General Motors, which made its first appearance in 1976 (Backaitits and Mertz, 1993), and consists of a multi-body system (see Figure 7.2). These models and dummies can simulate the time history of head motions and forces applied to the human neck during impulse excitation. They were not optimised to predict or simulate head-neck responses to other excitations, such as low frequency random vibration.

7.2.2 Whole body biodynamical models

The head-neck complex can also be presented in some whole-body biodynamic models. These models represent mainly the response of the seated body to vertical vibration or shock. Mechanical models can represent the body by mass, spring, and damper systems and predict the apparent mass (e.g., Wei and Griffin, 1998; Matsumoto and Griffin, 2001), driving point impedance (e.g., Boileau and Rakheja, 1998), or the transmissibility to

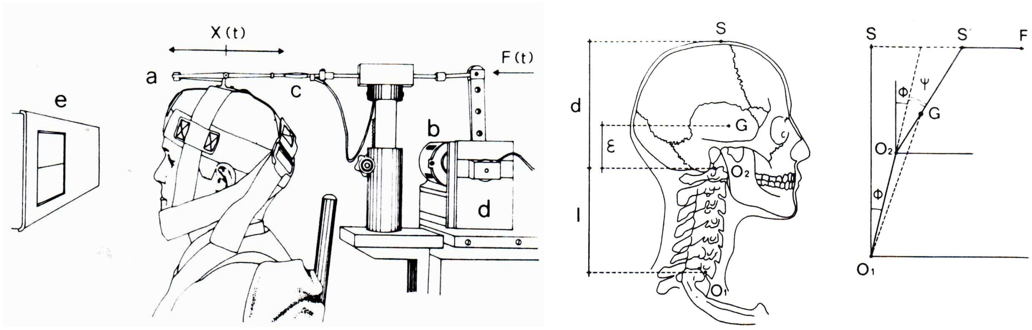


Figure 7.3 On the left experimental set-up. On the right geometry of the model (taken from Viviani and Berthoz, 1974).

different parts of the body (e.g., Dupuis, 1989; Fritz, 1997). Some models take in consideration the seat cushion (e.g., Qassem, 1996; Verver and Hoof, 2002). Numerical models, representing the apparent mass of the seated human body, have also been developed from models used to predict human response to short duration shocks and high magnitude vibration (e.g., Kitazaki and Griffin, 1997).

7.2.3 Lumped parameters head-neck models

Viviani and Berthoz (1974) measured the response of the head-neck system to small forces applied to the head through an array of belts. The torso of the subject was immobilized and subjects were asked to resist the motions. The corresponding forces and the displacements of the head were measured. A two degree-of-freedom model with two centres of rotation localised at the vertebrae T1 and C1 was developed to fit the experimental results (see Figure 7.3). Similar head-neck models have been used by Fard *et al*. (2003) to predict the transfer function between the trunk horizontal acceleration and the head angular velocity (see Figure 7.4), by Harvey (1990) to predict the seat-to-head transmissibility, and by Jex and Magdaleno (1978) to predict aircraft pilot performance with different tasks.

7.3 HEAD-NECK MODEL FOR BODY SEATED ON A RIGID SEAT

7.3.1 Introduction

The objectives of the head-neck model to be developed here is to predict head and neck motions and identify which type of head motion might generate subjective discomfort time-dependency (SDTD). Lumped parameter head-neck models can predict head motions and also describe the type of head motion produced at the resonance (using analysis of the mode shapes).

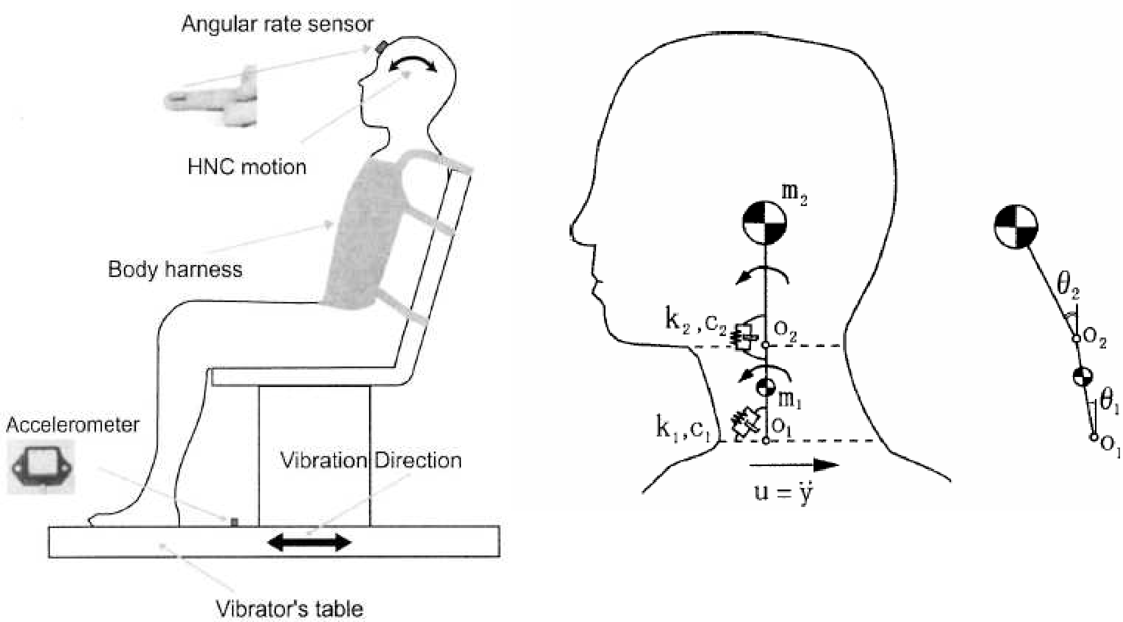


Figure 7.4 On the left experimental set-up. On the right geometry of the model (taken from Fard *et al*., 2003).

In a first approach, a head-neck model was designed to predict the head motions for a subject seated on a rigid seat. Using a rigid seat allows the identification of the head and neck parameter values without being corrupted by the dynamic properties of the car seat. Therefore a range of values can be assigned to the head and neck parameters before the applicability of the model, with the inclusion of a car seat, is improved.

This section presents a three degree-of-freedom lumped parameter head-neck model. This model was optimised with seat-to-head transmissibility data (from Paddan and Griffin 1988) measured with one subject seated on a rigid seat with backrest (without a trunk harness). Head and neck parameters (stiffness and damping) were compared with parameters obtained with the head and neck models presented in Figure 7.3 and 7.4 (Viviani and Berthoz, 1974; Fard *et al.*, 2003).

7.3.2 Methodology

7.3.2.1 Objective

The objective of this study is to develop a model predicting head and neck motions due to fore-and-aft excitations. The fore-and-aft direction of excitation was investigated because it is the direction that produced the greatest subjective discomfort time-dependency (for most of the investigated stimuli). It is also the direction whose effects of frequency on

SDTD were the most consistent through the different waveform studies (see Chapter 3). During fore-and-aft excitation, the heads of seated subject respond in the mid-sagittal plane. Therefore, the model is required to predict head motions in the fore-and-aft, pitch and vertical directions. The relative motions of the upper back, neck and head can be predicted by the calculation of the mode shapes (eigen values and eigen vectors of the model).

Once the model is designed, the neck and head parameters of the model need to be determined. These parameters can be identified more appropriately when the dynamic properties of the car seat are not involved. Therefore, the parameters of the model will be identified and optimised using the seat-to-head transmissibility data of a single subject seated on a rigid seat with back in contact with a rigid backrest (Paddan and Griffin, 1988).

7.3.2.2 Hypothesis

It is hypothesised that the response of the head-neck system could be adequately represented by two rigid bodies: the head and the neck, with the head linked to the neck at the vertebrae C1 by a spring and damper connection, and the neck linked to the trunk at vertebrae T1 by a similar spring and damper connection. A third degree-of-freedom can be added to represent the effect of the backrest on the body dynamic responses.

The neck and head inertia and visco-elastic parameters will be defined by fitting the model to the seat-to-head transmissibility measured with a subject seated on a rigid seat.

7.3.2.3 Use of experimental seat-to-head transmissibility data

The seat-to-head transmissibility used as a target for the model was taken from one subject during the investigation of the intra-subject variability experiment conducted by Paddan and Griffin (1988). A brief summary of their procedure was provided in Section 6.2.4.

7.3.2.4 Modelling and identification

A double inverted pendulum with two degrees-of-freedom was considered as a physical model for the head-neck system. A third degree-of-freedom was added to simulate the response of the back to the backrest excitation. The two centres of rotation of the head-neck system were assumed to be at the junction of C7 and T1 and at the junction of C0 and C1 in the cervical spine. The head and neck were represented by two lumped masses. The centre of mass of the neck was assumed to be at the midpoint between the two centres of rotation. In a resting position (initial position), the centre of mass of the head was assumed to be in line with the two centres of rotation and the centre of mass of the neck (the centres of mass were aligned vertically above each other). The model assumed that the displacements of the head relative to the neck, and the displacements of the neck relative to the trunk, were small, allowing the use of linear equations. The model is shown in Figure 7.5.

The model leads to three transfer functions: $\frac{\theta_3(f)}{Y(f)}$, $\frac{\theta_2(f)}{Y(f)}$ and $\frac{X_1(f)}{Y(f)}$. However these transfer functions cannot be directly compared to the seat-to-head transmissibility shown in Figure 7.3. The pitch, vertical and fore-and-aft seat transmissibility, respectively denoted as $\frac{\Phi(f)}{Y(f)}$, $\frac{Z(f)}{Y(f)}$ and $\frac{X(f)}{Y(f)}$ can be expressed in the form:

$$\frac{\Phi(f)}{Y(f)} = \frac{\theta_3(f)}{Y(f)}$$

$$\frac{Z(f)}{Y(f)} = d\,\frac{\theta_3(f)}{Y(f)}$$

with *d* the distance between the accelerometer location and the centre of gravity of the head, and

$$\frac{X(f)}{Y(f)} = \frac{X_1(f)}{Y(f)} - 2l_1\frac{\theta_2(f)}{Y(f)} - l_2\frac{\theta_3(f)}{Y(f)}$$

with :

X_1(f): acceleration [m.s^{-2}] in the fore-and-aft direction of the mass m_1 representing the upper-back,

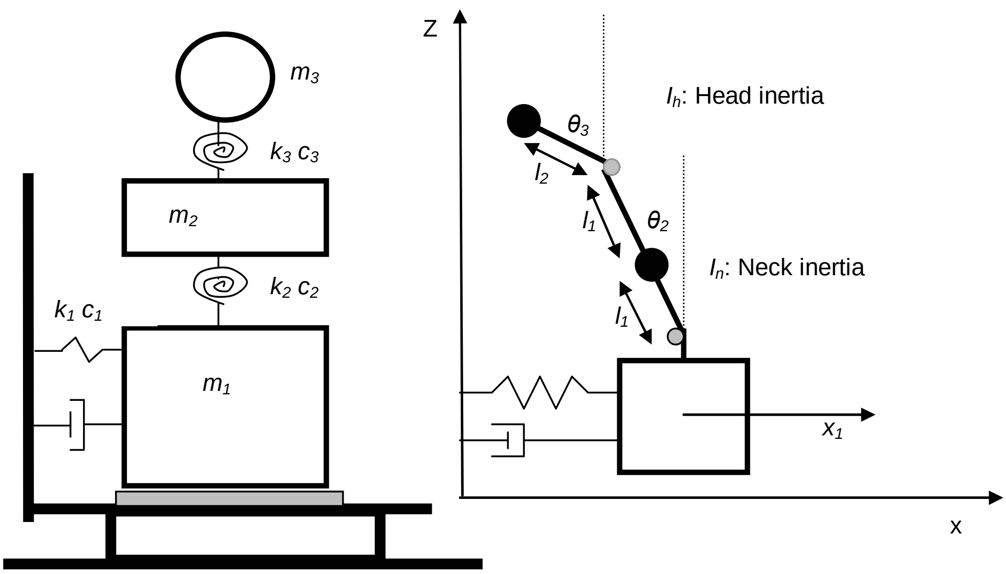


Figure 7.5 Lumped parameter model representing the response of the head, neck and trunk to fore-and-aft excitation of the rigid seat.

θ_2(f): pitch angular acceleration [rad.s^{-2}] of the centre of mass of the neck (m_2),

θ_3(f): pitch angular acceleration [rad.s^{-2}] of the centre of mass of the head (m_3),

Y(f) : fore-and-aft input acceleration [m.s^{-2}] applied to the mass m_1 representing the upper-back,

X(f): acceleration [m.s^{-2}] in the fore-and-aft direction of the mass m_3 representing the head,

Z(f): acceleration [m.s^{-2}] in the vertical direction of the mass m_3 representing the head,

Φ (f): pitch angular acceleration [rad.s^{-2}] of the mass m_3 representing the head,

l_1 distance [m] between the centre of rotation of the upper-back and neck and the centre of mass of the neck,

l_2 distance [m] between the centre of rotation of the neck and head and the centre of mass of the head.

The method used to identify the inertia and visco-elastic parameters of the model was constrained nonlinear optimization or non-linear programming (Powell, 1978). The MATLAB (7.2) function "fmincon" was used for this purpose. This function finds a constrained minimum of a scalar function of several variables starting from an initial estimate. An error function, which is the difference (in the frequency domain) between the experimental data and the data generated by the model, is produced. The MATLAB function, "fmincon" determines the minimum of the error function and generates the value of the corresponding model parameters.

The inertial characteristics (i.e. m_1, m_2, m_3, d, l_1, l_2, I_n, I_h) were initially selected from the literature (Viviani and Berthoz, 1974; Fard *et al.*, 2003, De Leva, 1996). As the method needs lower and upper limits for the values of the parameters, $\pm 30\%$ of the initial values were chosen as constraints. Only the mass m_1 of the trunk (or upper-back) was allowed a greater range because it was not known how much of the trunk was involved in the model. Initial and limiting values for the inertial parameters are shown in Table 7.1.

The visco-elastic parameters were allowed a greater range because they vary greatly from one study to another (Viviani and Berthoz, 1974; Jex and Magdaleni, 1978; Harvey, 1990; Fard *et al.*, 2003). The initial and limiting values of the visco-elastic parameters used for the optimization are shown in Table 7.1.

Table 7.1 Parameter values for the constrained non-linear optimisation.

PARAMETERS		Unit	Initial values	Lower constraints	Upper constraints
Inertial parameters	m_1	kg	2	1	60
	m_2	kg	1.07	0.75	1.39
	m_3	kg	4.31	3.1	5.6
	l_1	m	0.045	0.031	0.058
	l_2	m	0.075	0.052	0.975
	d	m	0.09	0.063	0.117
	I_n	$kg.m^2$	0.0012	0.00084	0.00156
	I_h	$kg.m^2$	0.05	0.035	0.065
Visco-elastic parameters	k_1	$N.m^{-1}$	1500	100	70000
	k_2	$N.rad^{-1}$	70	10	100
	k_3	$N.rad^{-1}$	70	10	100
	c_1	$N.s.m^{-1}$	200	10	1000
	c_2	$N.s.rad^{-1}$	1.5	0.01	5
	c_3	$N.s.rad^{-1}$	0.1	0.01	5

7.3.3 Results

7.3.3.1 Frequency response functions of the model

The frequency response functions provided by the model showed a good agreement with the experimental data. Figure 7.6 and Figure 7.7 compare the modulus and the phase of the measured transfer functions with those of the optimised dynamic model. The transfer functions provided by the model show, as in the experimental data, resonances around 1.5 Hz and 7.5 Hz.

7.3.3.2 Mode shapes

As the model was composed of three masses, springs and dampers, the transfer functions were expected to show three natural frequencies. The mode shapes (eigen vectors and eigen values) generated by the model can be calculated using the system equations without damping. The mode shapes of the model are defined by:

f_1 = 1.5 Hz with corresponding eigen vector $v_1 = \begin{bmatrix} -0.00 \\ 0.56 \\ 0.82 \end{bmatrix}$

f_2 = 7.6 Hz with corresponding eigen vector $v_2 = \begin{bmatrix} 0.08 \\ -0.52 \\ 0.85 \end{bmatrix}$

f_3 = 11.0 Hz with corresponding eigen vector $v_3 = \begin{bmatrix} 0.02 \\ 0.89 \\ -0.45 \end{bmatrix}$

The eigen vectors represent the relative displacements of the model variables contained in the state vector $\begin{bmatrix} X_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$. The natural frequencies (eigen values) can be affected by the damping, but the eigen vectors are independent of the damping.

The three eigen vectors show that the displacement of mass m_1, representing the trunk,

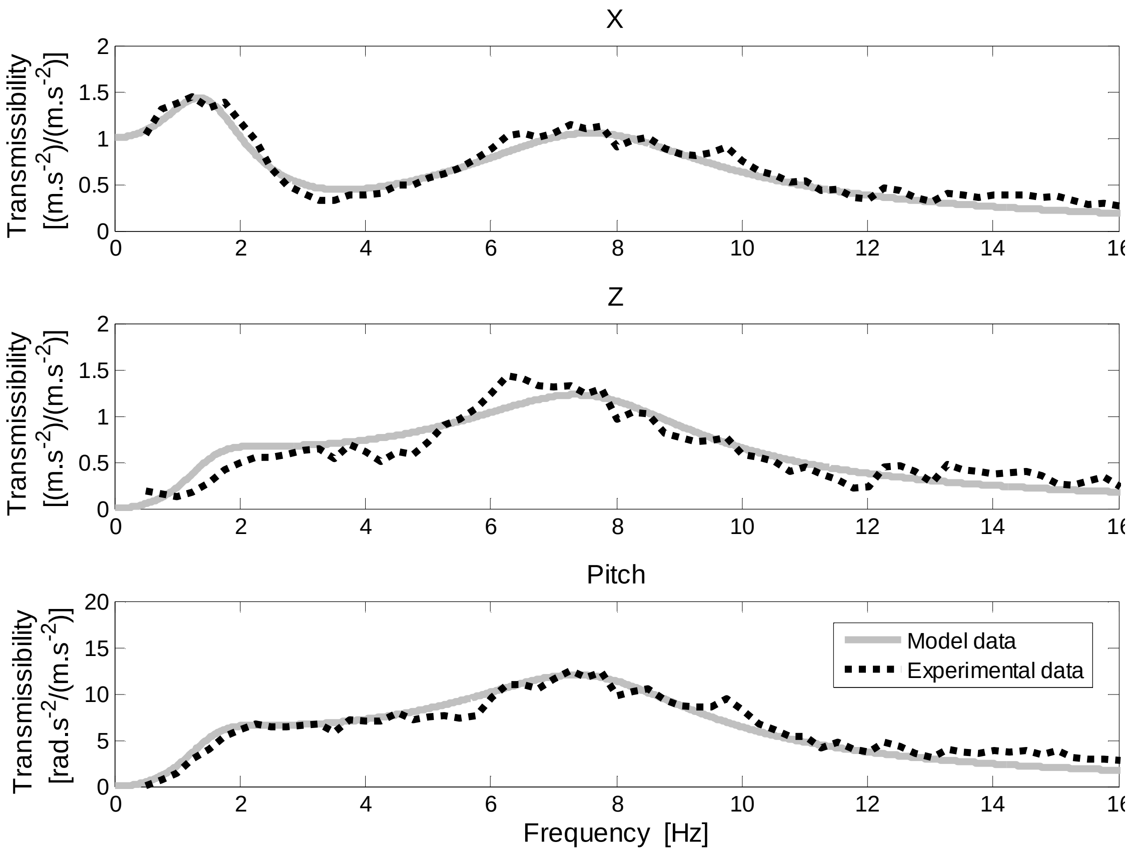


Figure 7.6 Moduli of the transfer functions produced by the model, and the experimental data measured by Paddan and Griffin, 1988 (Input: fore-and-aft acceleration at the rigid-seat-pan, output: head accelerations in the fore-and-aft, vertical and pitch directions).

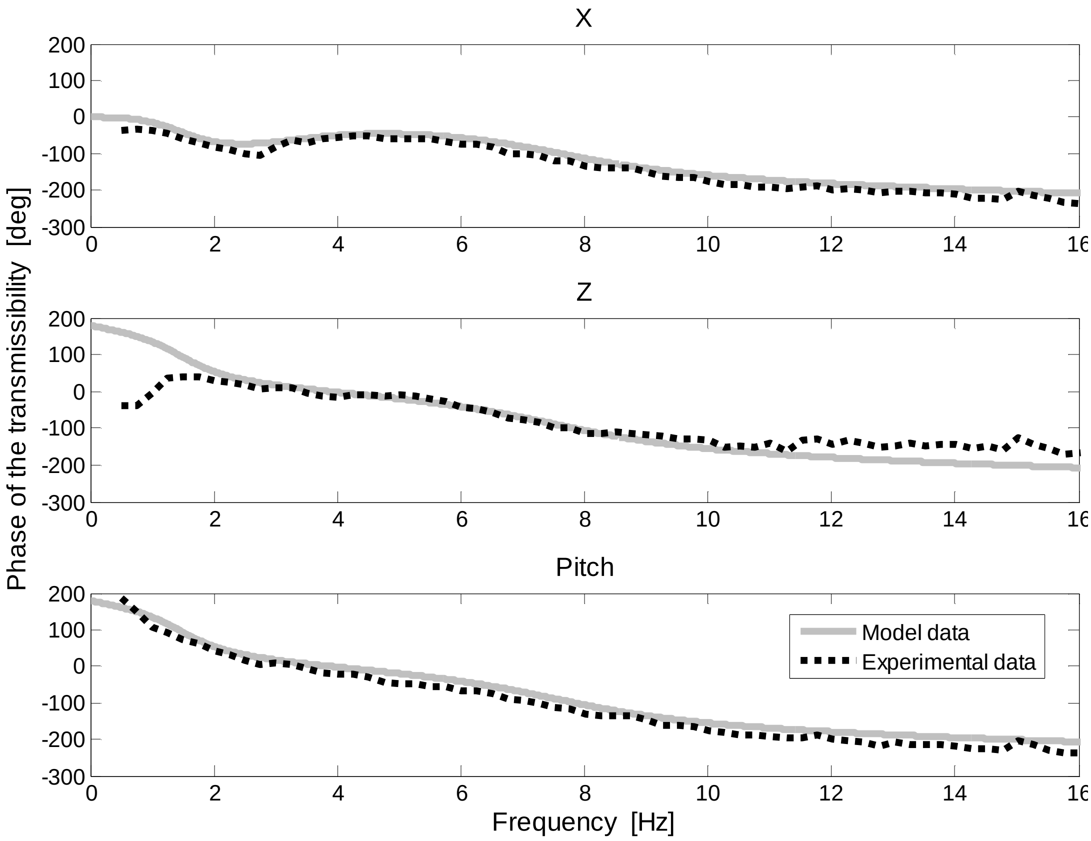


Figure 7.7 Phases of the transfer functions produced by the model, and the experimental data measured by Paddan and Griffin, 1988 (Input: fore-and-aft acceleration at the rigid-seat-pan, output: head accelerations in the fore-and-aft, vertical and pitch directions).

was much smaller relative to the displacement of mass m_2 and mass m_3 representing, respectively, the masses of the neck and the head.

The first mode, f_1, v_1, describes the body motion occurring at the first resonance observed around 1.5 Hz in the seat-to-head transmissibility data. At this resonance, the head and neck were moving in phase relative to the trunk. There was a small relative displacement between the head and the neck.

The second mode (f_2, v_2) and third mode (f_3, v_3) describe the body motion occurring at the second resonance observed around 7.5 Hz on the seat-to-head transmissibility data. It seems that the second resonance is due to two close natural frequencies. Due to the relative displacement of the trunk, which is negligible, the second and third modes describe a similar motion of the body. The head is moving out of phase with the neck.

Table 7.2 Parameter values calculated with the constrained non-linear optimisation.

PARAMETERS		Unit	Optimal values
Inertia Parameters	m_1	kg	19.85
	m_2	kg	1.18
	m_3	kg	4.15
	l_1	m	0.056
	l_2	m	0.092
	d	m	0.10
	In	$kg.m^2$	0.00089
	Ih	$kg.m^2$	0.056
Visco-elastic Parameters	k_1	$N.m^{-1}$	56177
	k_2	$N.rad^{-1}$	37.88
	k_3	$N.rad^{-1}$	45.69
	c_1	$N.s.m^{-1}$	522
	c_2	$N.s.rad^{-1}$	2.97
	c_3	$N.s.rad^{-1}$	0.70

Compared to the first mode, where the head and neck were moving relative to the trunk, the second and third mode show that the head is moving relative to the neck.

7.3.3.3 Model parameter values

The parameters calculated by the constrained non-linear optimisation method are presented in Table 7.2.

The effects of each visco-elastic parameter on the fore-and-aft seat-to-head transmissibility were calculated by generating the seat-to-head transmissibility with one parameter varying between -30% and +30 % of its optimal value. The fore-and-aft seat-to-head transmissibility was chosen because this direction shows clearly the effect of each visco-elastic parameter on each of the three resonances calculated by the model. The calculation was repeated for each parameter and the results are shown in Figures 7.8 and 7.9.

By observing Figures 7.8 and 7.9, it can be noticed that:

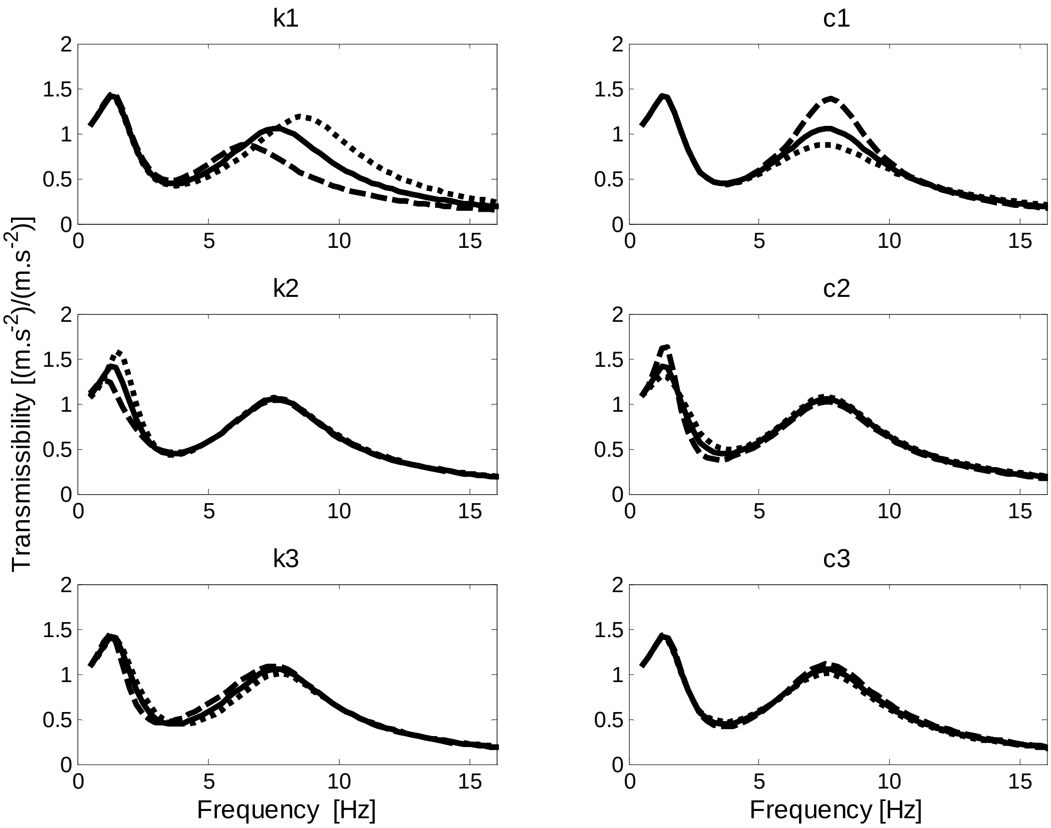


Figure 7.8 Effects of each visco-elastic parameter on the modulus of the fore-and-aft seat-to-head transmissibility (with a rigid seat). The dotted line represents the transmissibility calculated with the optimum parameter value +30%. The dashed line represents the transmissibility calculated with the optimum parameter value -30%. The solid line represents the transmissibility calculated with the optimum value of the parameter.

- The first resonance observed around 1.5 Hz was due to the system m_2, c_2 and k_2, representing the neck and neck muscles and ligaments.
- The second resonance observed around 7.5 Hz was due to the system m_1, c_1, k_1, representing the trunk and the back tissues in contact with the backrest.
- Both resonances at 1.5 Hz and 7.5 Hz are slightly affected by the system m_3, k_3, c_3 representing the head and the muscles and ligaments linking the head to the neck.

7.3.4 Discussion

The three degree-of-freedom lumped parameter model presented in this study showed a good agreement with the experimental seat-to-head transmissibility data of a single subject. The model was able to represent accurately (from 0.5 Hz to 16 Hz) the frequency

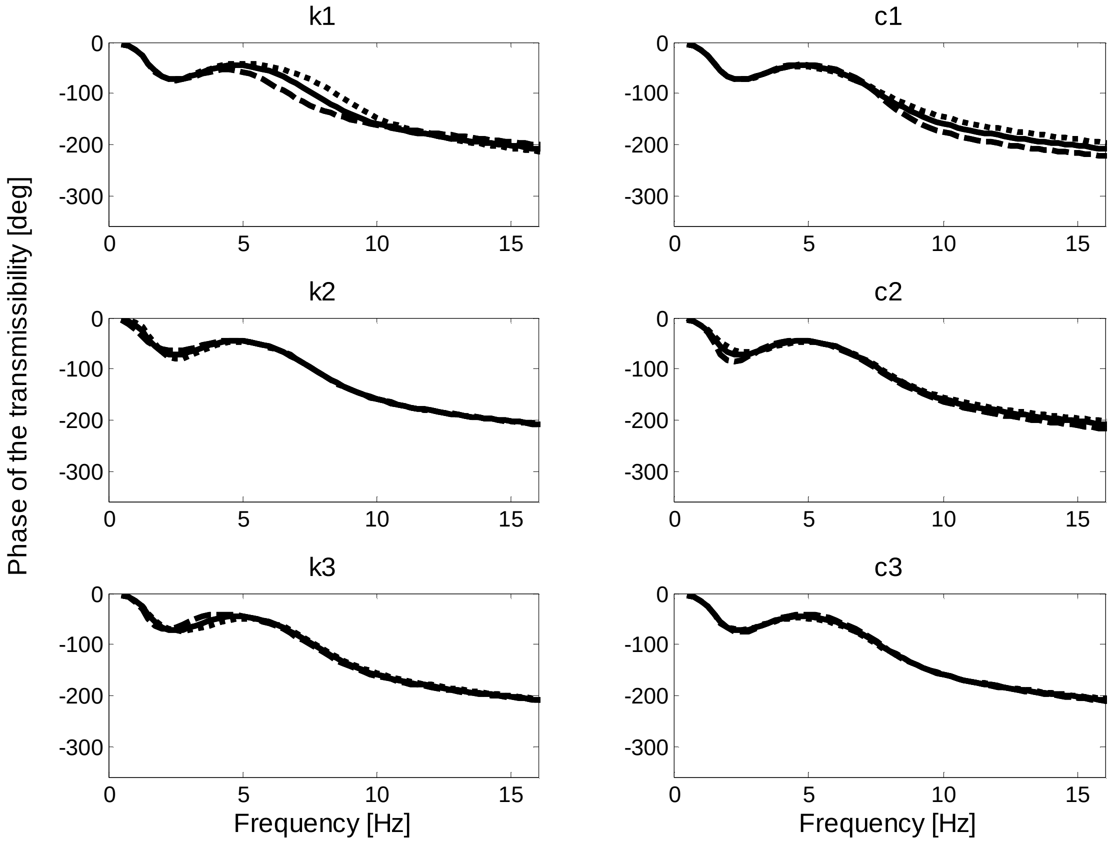


Figure 7.9 Effects of each visco-elastic parameter on the phase of the fore-and-aft seat-to-head transmissibility (with a rigid seat). The dotted line represents the transmissibility calculated with the optimum parameter value +30%. The dashed line represents the transmissibility calculated with the optimum parameter value -30%. The solid line represents the transmissibility calculated with the optimum value of the parameter.

response functions (both modulus and phase) from fore-and-aft acceleration at the seat to fore-and-aft, vertical and pitch acceleration at the head.

Figures 7.8 and 7.9 allow a consideration of the precision required of the visco-elastic parameters in the model. By varying parameters k_3 and c_3 from -30% to +30% of their optimum values, the seat-to-head transmissibility did not show a large variation. This means that values for the parameters k_3 and c_3 cannot be determined with great accuracy. However, by varying the values of parameters k_1, c_1 and k_2, c_2, from -30% to +30%, the seat-to-head transmissibility varied greatly, so the optimum values representing the dynamic characteristics of the upper trunk and neck are more accurately defined than the dynamic parameters of the head.

Most double inverted pendulum models of the head-neck system in the literature predict seat-to-head transmissibility with the trunk fixed rigidly to the backrest. Three studies with similar models have produced different visco-elastic parameters of the neck (Viviani and Berthoz, 1974; Jex and Magdaleno, 1978, Fard *et al.*, 2003). As none of these models included the effect of the backrest, only the visco-elastic parameters of the head (k_3, c_3) and neck (k_2, c_2) can be compared. Viviani and Berthoz considered the dynamic stiffness and damping between 0.1 to 10 Hz. The visco-elastic parameters obtained in this study are compared with those in the literature in Table 7.3.

The three studies used similar double inverted pendulum models. The differences in their visco-elastic parameters might come from the extent to which the subjects were in contact with the backrest. Also, the outputs of the models differed in each study. In the study by Viviani and Berthoz, the model was designed to predict the transfer function defined by the displacement of the head divided by the force applied to the head. The model by Fard *et al*. predicted the ratio between the head angular velocity and the trunk horizontal acceleration. The optimisation method may also have differed in each case. Although the values of the parameters differ greatly from one study to another, there is a similar order of magnitude for the visco-elastic parameters.

Compared to previous models, the current model predicts moduli and phases of the seat-to-head transmissibility. Where most models simulate only pitch acceleration, this model represents the pitch, fore-and-aft and vertical acceleration of the head due to fore-and-aft excitation of the seat over a wide frequency range.

The model describes the type of head motions produced at the resonance. The mode shapes indicate that the vibration is transmitted to the head by two mechanisms (two different relative motions of the head, neck and trunk). At the first resonance (at 1.5 Hz), the head and neck are moving in phase relative to the upper trunk. For the second and third mode (at 7.5 Hz and 11.0 Hz), the head is moving out of phase with the neck. For all three modes the displacement of the upper back is negligible compared to the displacement of the head and neck.

Table 7.3 Comparison of the visco-elastic parameters of the neck obtained in this study with the previous literature.

Visco-elastic parameters	Current study	Viviani and Berthoz	Jex and Magdaleno	Fard *et* al.
k_2 [N.rad^{-1}]	37.88	from 6 to 100	50	15.57
k_3 [N.rad.$^{-1}$]	45.69	from 6 to 100	15	10.45
c_2 [N.s.rad.$^{-1}$]	2.97	from 0.1 to 5	0	0.358
c_3 [N.s.rad.$^{-1}$]	0.70	from 0.1 to 5	0.126	0.266

Probably the neck and head parameters would not have been the same and so accurate if the model was fitted directly with the floor-to-head transmissibility measured on a car seat. Using a rigid seat allowed setting the head and neck parameters without the influence of the dynamic properties of the car seat. The dynamic properties of the car seat are expected to affect the values of the model parameters k_1 and c_1, but the other model parameters should not be greatly affected.

Investigating the relationship between the subjective discomfort time-dependency (SDTD) presented in Chapter 3, the phasic and tonic muscle activity presented in Chapter 5 and the mode shapes at the resonances, could indicate, for each identified type of head motion (eigen vectors), the content of phasic and tonic neck muscle activity required and therefore estimate the SDTD. The mode shapes may provide, as well as the backrest-to-head transmissibility, a tool to estimate the SDTD.

7.4 HEAD-NECK MODEL FOR BODY SEATED ON A CAR SEAT

7.4.1 Introduction

The three degree-of-freedom lumped parameter head-neck model, developed in Section 7.3, seems to provide an accurate tool for predicting head motions for subjects seated on a rigid seat. This section investigates the applicability of the model to the prediction of transmissibility and mode shapes for head motions of subjects seated on a car seat.

7.4.2 Methodology

7.4.2.1 Objective

This study was designed to achieve the main objective of Chapter 7, which is the identification of head motions expected to cause the subjective discomfort time – dependency (SDTD). The lumped parameters of the head-neck model developed in Section 7.3 and presented in Figure 7.5 are used to predict head motions of subjects seated on a car seat. Head motions producing SDTD may be estimated from the backrest-to-head transmissibility (through the neck muscle activity) as presented in Chapter 6. Section 7.3.4 suggested that the relationship between SDTD, neck muscle activity and the mode shapes may also help to determine the type of head motion causing the discomfort time-depenency.

The head and neck model parameters determined previously (see Table 7.2) will be refined (i.e. a small variation of the value of the determined parameters will be allowed) and the parameters k_1 and c_1 will be optimized using the median of the floor-to-head transmissibility data measured with 12 seated subjects (on a conventional car seat) exposed to broadband random fore-and-aft excitation (at the floor) at 0.6 $m.s^{-2}$ r.m.s. (see Chapter 6). The parameters found during model optimization, will be used to calculate the mode shapes. The backrest-to-head transmissibility will be calculated from the predicted floor-to-head transmissibility and the known backrest transmissibility. A possible solution to predict the floor-to-head transmissibility for any car seat with a known backrest transmissibility will be suggested.

7.4.2.2 Hypothesis

Chapter 6, Section 6.7.4 (Figure 6.15) showed that the dynamic properties of the backrest affected greatly the floor-to-head transmissibility. It is expected that the dynamic properties of a car backrest will affect mainly the parameters k_1 and c_1 of the model presented in Figure 7.5. Relative to a rigid backrest, the value of k_1 should be reduced for a car backrest. The parameters of the head and neck should not be altered greatly.

Chapter 6, Section 6.7.4.3, Figure 6.18 showed that the backrest-to-head transmissibility can be well predicted from the measured floor-to-head transmissibility and the measured backrest transmissibility. It is expected that the backrest-to-head transmissibility can be estimated from the predicted floor-to-head transmissibility and the measured backrest transmissibility.

The mode shapes calculated with the head and neck model presented in Figure 7.5 showed that two different types of head motion may appear at the resonances. According to the measured floor-to-head transmissibility (see Chapter 6, Section 6.6, Figure 6.6) and the results of the subjective study (see Chapter 3), the model should present resonances around 1 Hz and around 4 Hz, with two different types of head motion.

The dynamic parameters k_1 and c_1, relative to the mass m_1, should influence the motion of the upper-back relative to the vibrator platform acceleration. Backrest transmissibility is the ratio of the acceleration at the interface between the backrest and the back of a subject to the acceleration of the vibrator platform. The acceleration of the mass m_1 should have some similarity with the acceleration of the interface between the backrest and the back of a subject. Therefore the degree of freedom represented by c_1 and k_1 may produce an estimate of the backrest transmissibility. This hypothesis will be tested to investigate whether the parameters k_1 and c_1 may be calculated from the measure of backrest transmissibility. This will allow the model to predict the floor-to-head transmissibility for any type of seat from the known dynamic properties of the backrest.

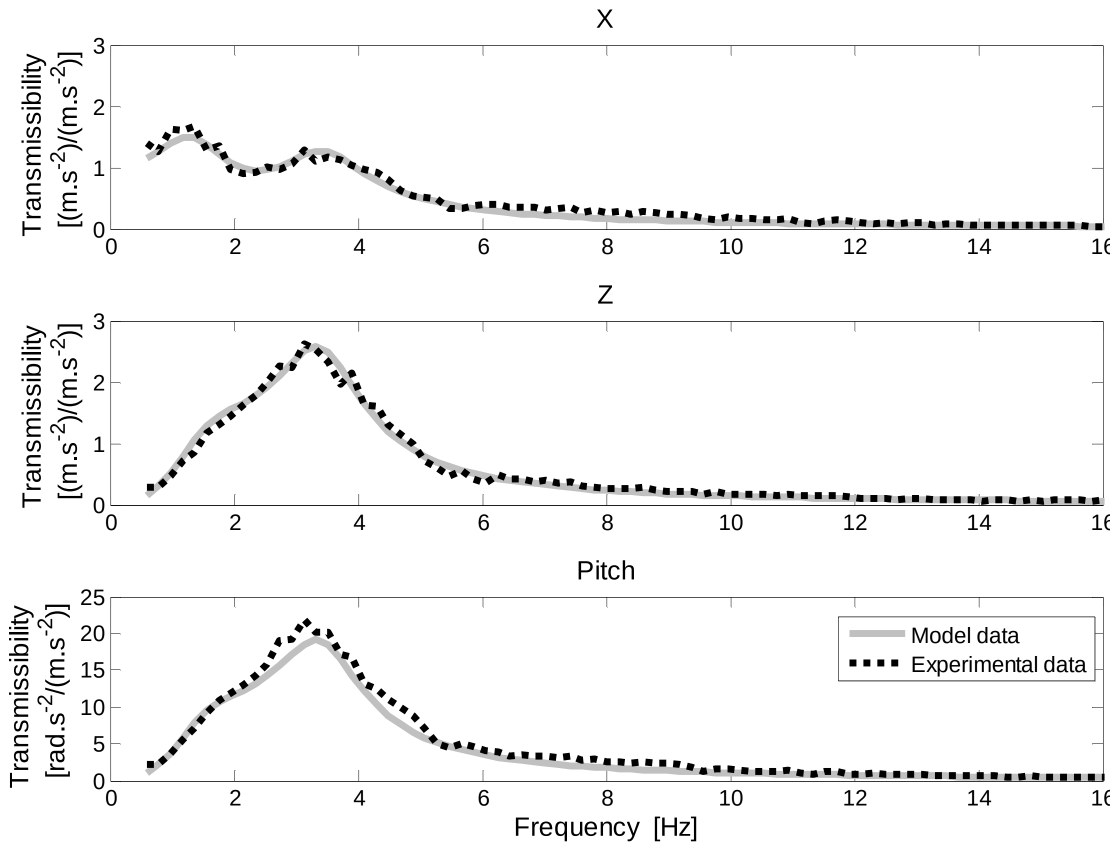


Figure 7.10 Moduli of the transfer functions produced by the model, and the experimental floor-to-head transmissibility measured in Chapter 6 (Input: fore-and-aft acceleration at the vibrator platform, output: head accelerations in the fore-and-aft, vertical and pitch directions).

7.4.2.3 Model optimization and identification

The model employed is that presented in Figure 7.5. The dynamic parameters c_1 and k_1 affect mainly the motion of the upper-back of mass m_1 relative to the platform acceleration. In Section 7.3, because the backrest was rigid, the parameters c_1 and k_1 represented the dynamic properties of the contact between the rigid backrest and the upper-back of the subjects (which mainly includes the stiffness and damping of the human tissues of the back). In this section, because the backrest was not rigid, c_1 and k_1 represent both the dynamic properties of the backrest and the contact between the car backrest and the back of the subjects (c_1 and k_1 represent the dynamic properties of everything that exists between the platform and the upper-back, including the back tissues of the subjects). As hypothesized, the parameters c_1 and k_1 are expected to vary greatly due to the dynamic properties of the backrest. The parameters related to the head and neck determined in

Section 7.3, with a rigid seat, were used as the initial values. For the optimization process, the parameters c_1 and k_1 were allowed a wide range of variation, whereas the neck and head parameters were allowed a smaller range of variation.

The model parameters were optimized using the median of the moduli and phases of the floor-to-head transmissibility (fore-and-aft, vertical and pitch motions of the head) measured on 12 subjects seated on a car seat (see Chapter 6, Section 6.6, Figure 6.6).

The optimization method used is identical as the one presented in Section 7.3.2.4 (non-linear optimisation or non-linear programming by Powell, 1978). The MATLAB (7.2) function "fmincon" was used for this purpose. This function determines the minimum of an error function and generates the value of the corresponding model parameters.

7.4.3 Results

7.4.3.1 Frequency response function of the model

The frequency response functions, provided by the model, showed a good agreement with the experimental transmissibilities obtained with a car seat. Figure 7.10 and Figure 7.11 compare, respectively, the modulus and the phase of the measured transfer functions with those of the optimized dynamical model. The transfer functions provided by the model show (as in the experimental data) resonances around 1.5 Hz and 3.5 Hz. The phase data tend to be less accurate as the frequency increases. This may be due to the 'unwrapping' procedure used to observe the phase continuously: as the frequency increases error is added.

7.4.3.2 Mode shapes

The mode shapes (eigen vectors and eigen values) generated by the model can be calculated using the system equations without damping. The mode shapes of the model are defined by:

f_1 = 1.4 Hz with corresponding eigen vector $v_1 = \begin{bmatrix} -0.00 \\ 0.46 \\ 0.89 \end{bmatrix}$

f_2 = 3.5 Hz with corresponding eigen vector $v_2 = \begin{bmatrix} -0.10 \\ -0.04 \\ -0.99 \end{bmatrix}$

f_3 = 6.9 Hz with corresponding eigen vector $v_3 = \begin{bmatrix} -0.02 \\ -0.83 \\ 0.55 \end{bmatrix}$

The first mode, f_1, v_1, describes the body motion occurring at the first resonance observed around 1.5 Hz in the seat-to-head transmissibility data. At this resonance, the head and neck were moving in phase relative to the upper-back. There was a small relative displacement between the head and the neck. At this frequency the backrest did not affect the transmission of the vibration (X_1 = 0.00 in the eigen vector V_1). This mode is similar to the first mode observed for the rigid seat (see Section 7.3.3.2).

The second mode, f_2, v_2, describes the body motion occurring at the second resonance observed around 3.5 Hz in the floor-to-head transmissibility data. As described in Chapter 6, this resonance of the system head-neck is mainly due to the resonance of the car backrest (see Chapter 6, Figure 6.10). At this resonance, the upper back, neck and head are moving in phase probably due to the resonance of the backrest.

The third mode, f_3, v_3, describes the body motion occurring at 6.9 Hz. At this frequency the head and neck are moving out-of-phase. Relative to the head and neck, the upper-back is not moving.

The mode shapes showed two main types of transmission of the vibration from the upper body to the head. The relative head, neck and upper-back motions observed at 1.4 Hz represents the head and neck moving relative to the trunk. The second type of transmission of the vibration observed at 3.5 Hz and 6.9 Hz showed that the head moves relative to the neck and upper-back (i.e., greater head motion than neck motion at 3.5 Hz and out-of-phase motion of the head relative to the neck at 6.9 Hz).

This confirms what can be visually observed when seated subjects are exposed to fore-and-aft sinusoidal excitations at 1 Hz and 4 Hz. With 1-Hz sinusoidal fore-and-aft excitation, the head and neck of the subject moved relative to the upper-back. At 4 Hz, his head moved relative to his neck.

7.4.3.3 Model parameter values

The parameters calculated by the constrained non-linear optimisation method are presented in Table 7.4.

The effects of each visco-elastic parameter on the fore-and-aft floor-to-head transmissibility were calculated by generating the floor-to-head transmissibility with one parameter varying between -30% and +30 % of its optimal value. The fore-and-aft floor-to-head transmissibility was chosen because this direction makes it possible to see most clearly the effect of each visco-elastic parameter on each of the three resonances calculated by the model. The calculation was repeated for each parameter and the results are shown in Figures 7.12 and 7.13.

By observing Figures 7.12 and 7.13, it can be noticed that:

- The first resonance observed around 1.5 Hz was due to the system m_2, c_2 and k_2, representing the neck and neck muscles and ligaments.
- The second resonance observed around 3.5 Hz was due to the system m_1, c_1, k_1, representing, the car backrest, the upper-back and the back tissues in contact with the backrest.
- The third resonance, at 6.9 Hz, is not directly observable on the floor-to-head transmissibility. The system m_3, k_3, c_3 representing the head and the muscles and

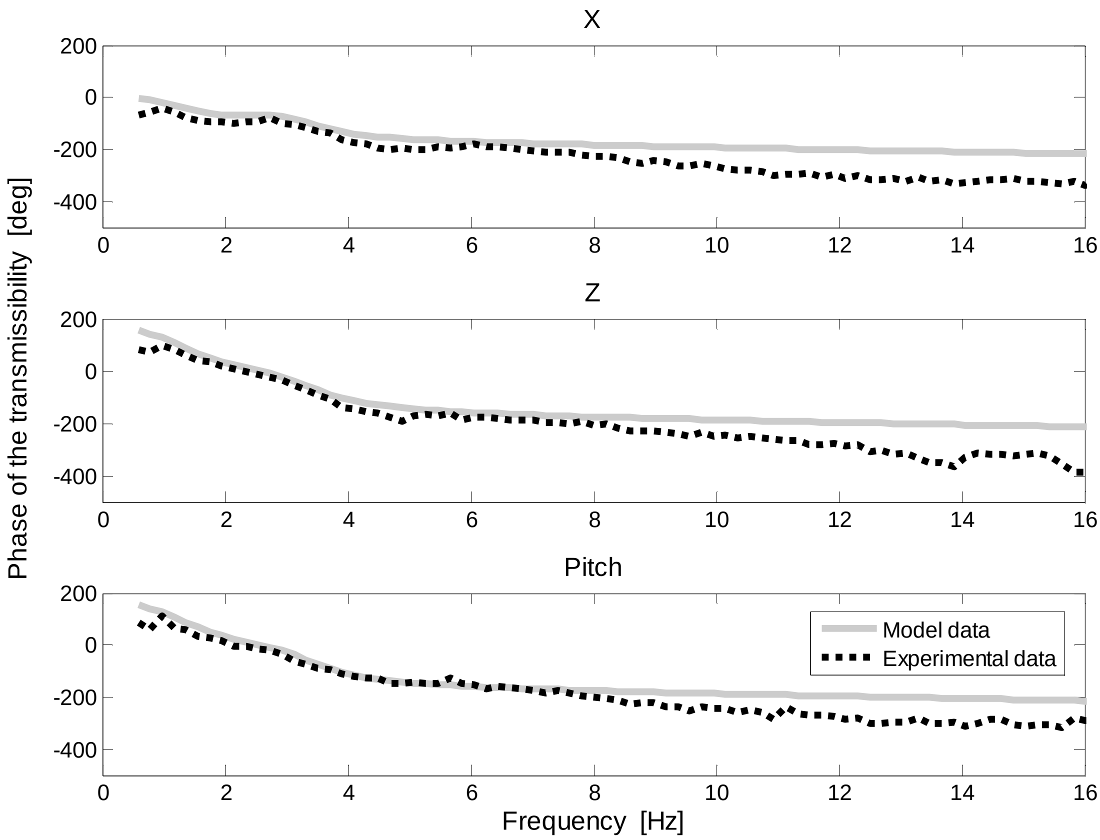


Figure 7.11 Phases of the transfer functions produced by the model, and the experimental floor-to-head transmissibility measured in Chapter 6 (Input: fore-and-aft acceleration at the vibrator platform, output: head accelerations in the fore-and-aft, vertical and pitch directions).

Table 7.4 Parameter values calculated with the constrained non-linear optimisation.

PARAMETERS		Unit	Optimum Value obtained with a rigid seat	Optimum Value obtained with a car seat
Inertia Parameters	m_1	kg	19.85	19.2
	m_2	kg	1.18	1.3
	m_3	kg	4.15	4.61
	l_1	m	0.056	0.052
	l_2	m	0.092	0.072
	d	m	0.1	0.12
	In	$kg.m^2$	0.00089	0.00084
	Ih	$kg.m^2$	0.056	0.041
Visco-elastic Parameters	k_1	$N.m^{-1}$	56177	10758
	k_2	$N..rad^{-1}$	37.88	28.8
	k_3	$N.rad^{-1}$	45.69	16.2
	c_1	$N.m^{-1}.s$	522	181
	c_2	$N.s.rad^{-1}$	2.97	2.48
	c_3	$N.s.rad^{-1}$	0.7	0.44

ligaments linking the head to the neck affects slightly the resonances at 1.5 Hz and 3.5 Hz.

7.4.4 Discussion

The three degree-of-freedom lumped parameter model in Figure 7.5 allowed a good curve-fit of the seat-to-head transmissibility measured with a rigid seat and of the floor-to-head transmissibility measured with the car seat. The head and neck parameters obtained with the optimization of the floor-to-head transmissibility with a car seat were within 25% of the head and neck parameters obtained with the optimization of the seat-to-head transmissibility with a rigid seat. Only the parameter k_3, representing the stiffness between the head and neck varied more than 25%. It is possible that this parameter had not been defined accurately during the optimization of the seat-to-head transmissibility with a rigid seat. Figures 7.8 and 7.9 show that varying the optimal value of the parameter k_3 from -30 % to + 30 % did not affect greatly the seat-to-head transmissibility. This study suggests that the prediction of the head and neck dynamic parameters, used to calculate the predicted floor-to-head transmissibility, may be accurate within 25%. Probably, the

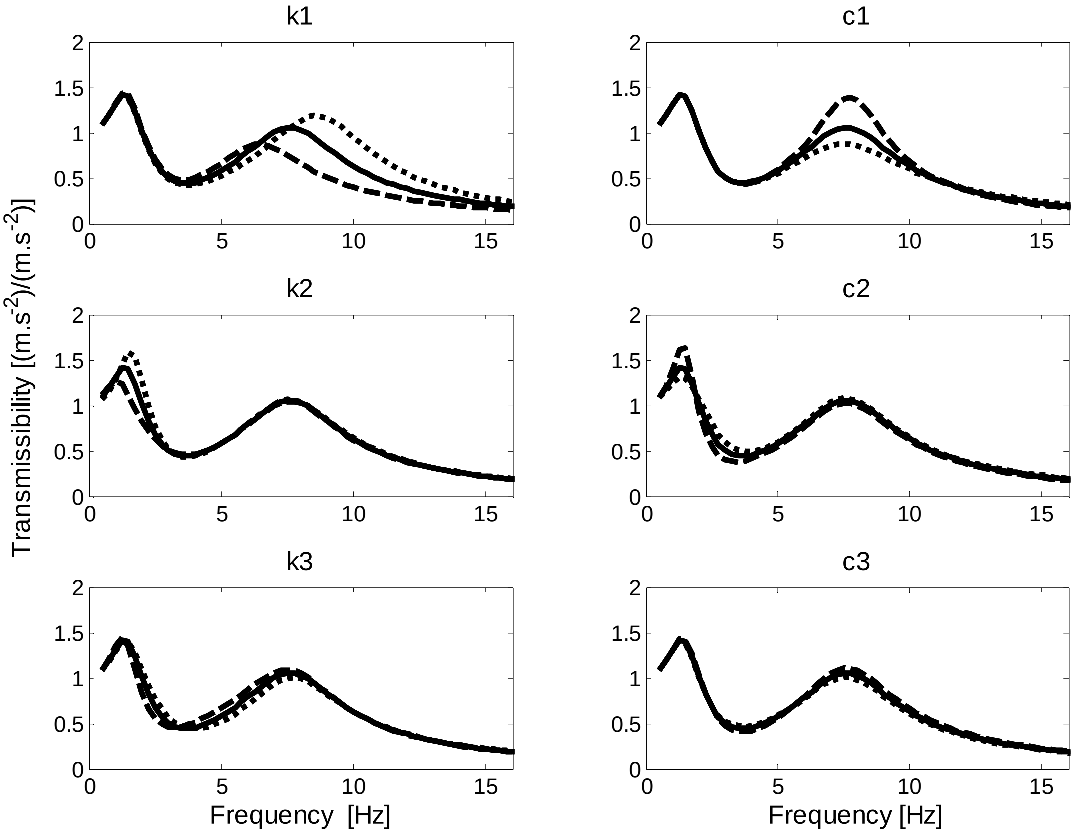


Figure 7.12 Effects of each visco-elastic parameter on the modulus of the fore-and-aft seat-to-head transmissibility (with a car seat). The dotted line represents the transmissibility calculated with the optimum parameter value +30%. The dashed line represents the transmissibility calculated with the optimum parameter value -30%. The solid line represents the transmissibility calculated with the optimum value of the parameter.

accuracy of the prediction may be improved if the subjects' postures had been identical for each seat investigated.

The dynamic parameters c_1 and k_1 determine the motion of the upper-back of mass m_1 relative to the platform acceleration. For a rigid backrest, the parameters c_1 and k_1 represent the dynamic properties of the contact between the rigid backrest and the upper-back. For a car seat backrest, c_1 and k_1 represent the contact between the car backrest and the upper-back and also the dynamic properties of the backrest. Therefore the great difference observed in Table 7.4 of the value of the parameters c_1 and k_1 measured between a rigid seat and a car seat was expected. The next section will investigate whether the optimized parameters c_1 and k_1 may be used to predict the backrest transmissibility.

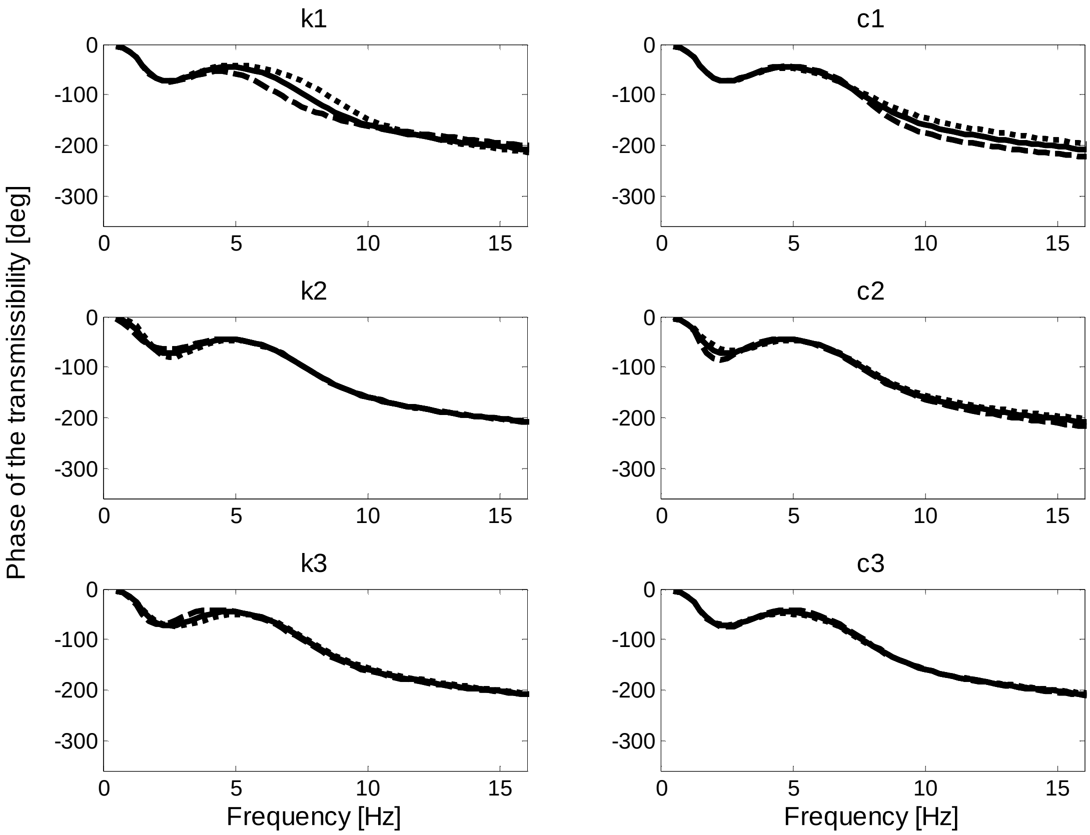


Figure 7.13 Effects of each visco-elastic parameter on the phase of the fore-and-aft seat-to-head transmissibility (with a car seat). The dotted line represents the transmissibility calculated with the optimum parameter value +30%. The dashed line represents the transmissibility calculated with the optimum parameter value -30%. The solid line represents the transmissibility calculated with the optimum value of the parameter.

The mode shapes (eigen values and eigen vectors) given by the model represent the relative motion of the different masses of the system: head, neck and upper back. The mode shapes obtained with optimisation of the seat-to-head transmissibility measured with a rigid seat and with optimisation of the floor-to-head transmissibility measured with a car seat gave similar types of head motions. The first mode at 1.5 Hz for the rigid seat and at 1.4 Hz for the car seat present the same type of head motion: motion of the head in phase with the motion of the neck and no motion of the upper-back relative to the head and neck. The second mode at 7.6 Hz for the rigid seat and at 3.5 Hz for the car seat presents different types of head motions: for the rigid seat the head and neck motion are out-of-phase and the upper-back moves slightly relative to the head and neck; for the car seat, the head, neck and upper-back motions are in phase but the head motion is greater than the neck and upper-back motions. The mode at 3.5 Hz is probably due to the resonance of the backrest observed in Figure 6.10. The third mode at 11.0 Hz with the rigid seat and at 6.9 Hz with the car seat presents the same type of head motion: motion of the head and motions of the neck are out-of-phase, the upper-back is almost not moving relative to the head and neck.

Chapter 3 showed that fore-and-aft excitation at 1 Hz generates lower subjective discomfort time-dependency (SDTD) than 4 Hz, 8 Hz, and 16 Hz. Chapter 5 showed that the ratio of the phasic neck muscle activity to the tonic neck muscle activity was greater at 1 Hz than at 4 Hz, 8 Hz, and 16 Hz. From the relationship between the SDTD and the phasic / tonic muscle activity ratio at each mode shape, it could be suggested that:

- In phase motions of the head and neck and no motion (relative to the head and neck) of the upper-back (mode at 1 Hz) seem to produce a low SDTD (by comparison with the SDTD measured at 1 Hz in Chapter 3). This type of head motion seems to generate mainly phasic activity (by comparison with the phasic / tonic muscle activity ratio measured at 1 Hz in Chapter 5). It could be suggested that when the neck follows the head motion, less tonic neck muscle activity may be required to control the head motion and therefore less discomfort time-dependency is produced.
- Greater motion of the head than the neck and a slight motion (relative to the head and neck) of the upper-back (mode at 3.5 Hz) seem to produce a higher SDTD (by comparison with the SDTD measured at 4 Hz in Chapter 3). This type of head motion seems to generate both tonic and phasic activity (by comparison with the phasic / tonic muscle activity ratio measured at 4 Hz in Chapter 5).
- Out-of-phase motions of the head and neck and a very low magnitude motion (relative to the head and neck) of the upper-back (mode at 6.9 Hz) seem to produce a higher SDTD (by comparison with the SDTD measured at 8 Hz in Chapter 3). This type of head motion seems to generate mainly tonic activity (in comparison with the phasic / tonic muscle activity ratio measured at 8 Hz in Chapter 5).

This study proposed three identified types of head motions that could be related to various discomfort time-dependencies. The mode shapes calculated from predicted floor-to-head transmissibility could inform whether the corresponding types of head motion predicted are one of the three previously identified types of head motions. From the basis of this, the mode shapes could be used as a tool to estimate SDTD.

7.5 PREDICTION OF THE BACKREST-TO-HEAD TRANSMISSIBILITY FROM THE PREDICTED FLOOR-TO-HEAD TRANSMISSIBILITY AND THE MEASURED BACKREST TRANSMISSIBILITY

Chapter 7 has suggested that subjective discomfort time-dependency (SDTD) may be estimated from the backrest-to-head transmissibility, through the phasic / tonic neck muscle activity ratio (if the vibration magnitude input at the backrest is known). Chapter 7 showed that the backrest-to-head transmissibility could be well estimated if the floor-to-head transmissibility is accurate and if the backrest transmissibility is known.

Figure 7.14 shows the measured modulus of the backrest-to-head transmissibility, presented in Chapter 6 (Figure 6.16) and the predicted modulus of the backrest-to-head transmissibility obtained by dividing the predicted modulus of the floor-to-head transmissibility (Figure 7.10) by the modulus of the backrest transmissibility measured in Chapter 6 (Figure 6.10).

This result shows that the backrest-to-head transmissibility can be reasonably well predicted, from the predicted floor-to-head transmissibility, with the known backrest transmissibility. On the basis that the backrest-to-head transmissibility may estimate SDTD through the neck muscle activity, engineers might use the predicted floor-to-head transmissibility to 'tune' the floor input vibration and the dynamic properties of the backrest to reduce the discomfort time-dependency.

7.6 PREDICTING THE FLOOR-TO-HEAD TRANSMISSIBILITY FROM THE DYNAMIC PROPERTIES OF THE BACKREST

The main drawback of the developed model is that the prediction of the floor-to-head transmissibility is accurate only for the seat investigated. Probably the parameters of the model would have to be adjusted each time a new seat is tested to provide an accurate floor-to-head transmissibility.

Section 7.4.4 suggested that the head and neck dynamic parameters could be estimated within 25%. It was also suggested that this accuracy may be improved if subjects maintain the same posture for each seat investigated. This section investigates whether the dynamic parameters c_1 and k_1, that determine the motion of the upper-back relative to the vibrator platform, may be obtained from the backrest transmissibility. If this is possible an estimated floor-to-head transmissibility may be obtained by the model using the optimized head and neck parameters (c_2, c_3, k_2 and k_3) and the parameters c_1 and k_1 obtained with the known backrest transmissibility.

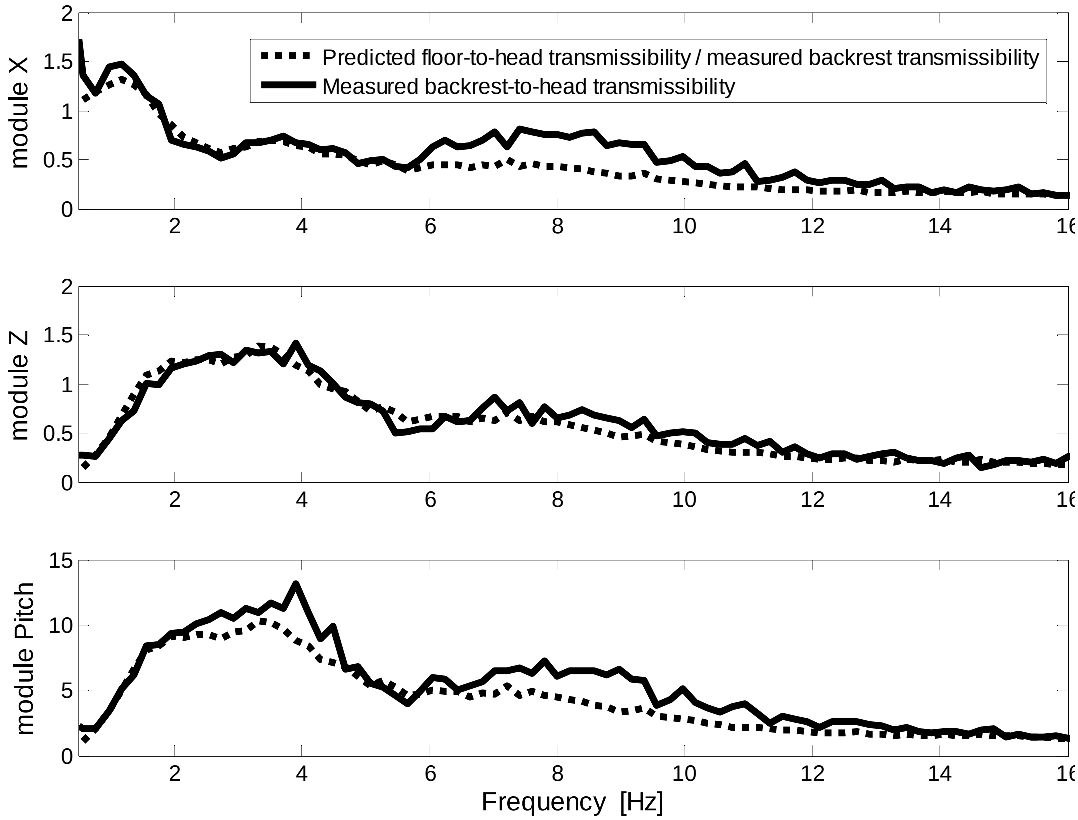


Figure 7.14 Effect of the car seat dynamic properties on the head motions (_ : Measured backrest-to-head transmissibility on a car seat with broadband random fore-and-aft excitation at 0.6 m.s^{-2} r.m.s. at the platform; **..** : predicted floor-to-head transmissibility divided by the measured backrest transmissibility measured in the fore-and-aft direction.

From the dynamic model presented in Figure 7.5 and the corresponding equations shown in Section 7.3.2.4, the model leads to three transfer functions, among them is $\frac{X_1(f)}{Y(f)}$.

where $X_1(f)$ is the acceleration of the upper-back and $Y(f)$ is the vibrator platform acceleration.

This function provided by the model may be close to the backrest transmissibility if the upper-back acceleration is similar to the acceleration at the interface between the car backrest and the back of the subject (which is generally where the backrest transmissibility is measured).

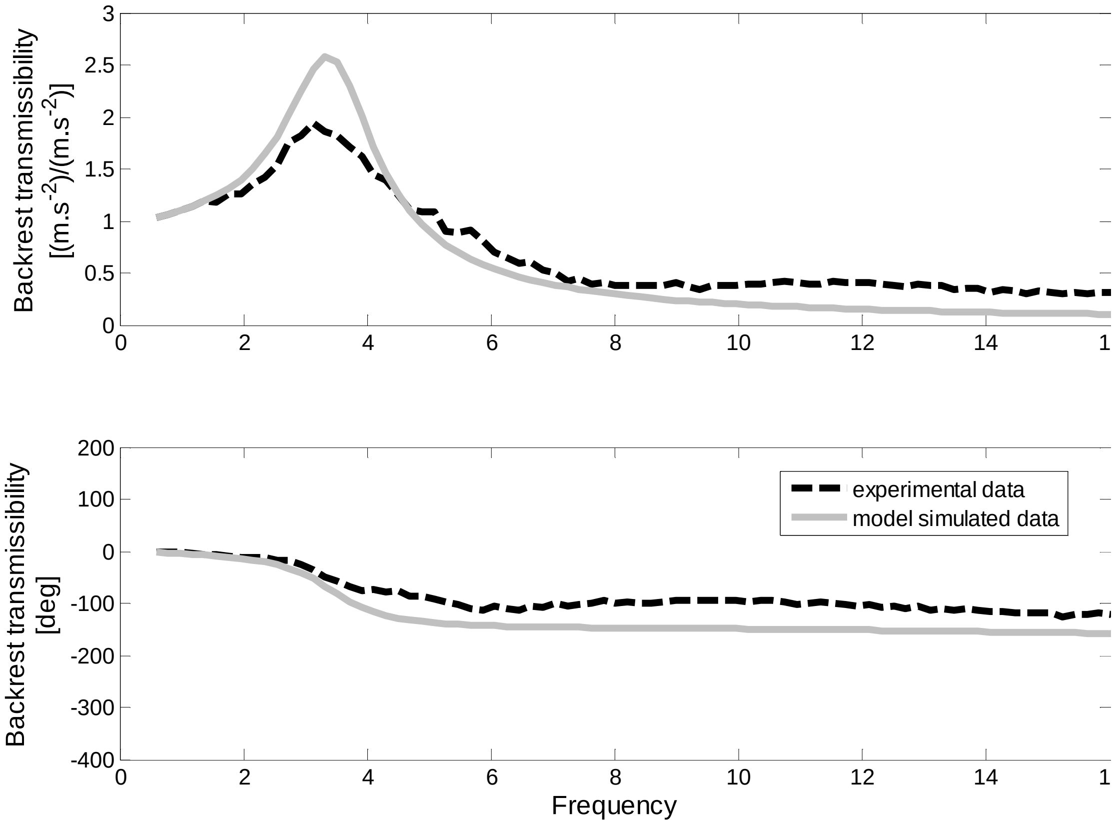


Figure 7.15 Comparison of the backrest transmissibility measured and predicted by the model

If the transfer function $\frac{X_1(f)}{Y(f)}$ is similar to the measured backrest transmissibility, it means that the dynamic properties of the backrest (dynamic stiffness and damping) could be directly injected in the model as c_1 and k_1.

Figure 7.15 compared the measured backrest transmissibility (see Chapter 6, Section 6.6.2, Figure 6.10) with the simulated backrest transmissibility obtained by the three degrees of freedom model ($\frac{X_1(f)}{Y(f)}$).

Figure 7.15 shows that the model predicts accurately the frequency of the resonance in the fore-and-aft seat backrest transmissibility but the damping was underestimated. Therefore the backrest transmissibility might not provide accurate values for the damping parameter c_1,, but the stiffness k_1 should be more accurate. The mode shapes of the model determined using the dynamic stiffness of the backrest should be accurate because they do not depend on damping.

7.7 CONCLUSION

This chapter investigated the pertinence of using a dynamic model of the head and neck response in predicting the subjective discomfort time dependency (SDTD).

The model showed that the head and neck dynamic parameters may be accurate within 25%. It was suggested that this accuracy could be improved if the subjects remain in the same posture for each seat tested. It also was shown that the backrest transmissibility may not provide an accurate value of the damping c_1, but the stiffness k_1 could be used to determine the mode shapes.

The analysis of the predicted mode shapes identified three types of head motions which may be related to various levels of discomfort time dependencies. Head motion in phase with the neck motion may imply that the head and neck motion are mainly controlled by phasic neck muscle activity and produce lower SDTD. With head motion greater than neck motion and with head and neck motions out-of-phase, the normalized phasic / tonic neck muscle activity may decrease (the magnitude of the tonic activity may increase) and discomfort increases at a faster rate.

The model is not, at this stage, able to predict accurately the backrest-to-head transmissibility for any seat, and therefore the corresponding estimated SDTD. However, the mode shapes may be accurately predicted from the optimised head and neck parameters and the known dynamics of the backrest. The predicted types of head motion may be compared with the three identified types of head motion presented in this study and the possible discomfort time-dependencies may be suggested.

8 DISCUSSION

8.1 INTRODUCTION

The objectives of the thesis were to investigate the effects of prolonged exposure to vibration on discomfort and to develop a model representing the different mechanisms involved in the subjective discomfort time dependency (SDTD).

The subjective results obtained with a new developed method suggested that neck muscle activity may be involved in the production of discomfort time-dependency. Neck muscle activity was measured during exposure to fore-and-aft sinusoidal excitation. The relationship between the subjective and physiological results tends to show that the discomfort time-dependency is greater when the neck muscles produced greater tonic, and less phasic, activity. It was hypothesized that the different content of phasic and tonic activity produced different types of head motion. The transmission of the vibration from the floor to the seat and to the head has been measured. A three degree-of-freedom lumped parameter model was designed and its parameters optimised to fit the measured floor-to-head transmissibility. The lumped parameter model has identified, through the relationship of the SDTD results and the mode shapes, three types of head motion corresponding to different discomfort time-dependencies. From the relationship between the measured backrest-to-head transmissibility and the neck muscle activity, it was suggested that the phasic component of the overall neck muscle activity may be estimated from the phase of the backrest-to-head transmissibility. It was also discussed if the magnitude of the tonic activity may be estimated from the modulus of the backrest-to-head transmissibility (when the input vibration at the backrest is known). From an engineering point of view, the prediction of SDTD from the known vibration input at the floor and the known dynamic properties of the backrest has been investigated. The results suggested that the mode shapes could be predicted for any seat from the known dynamic stiffness of the backrest. An accurate prediction of the backrest-to-head transmissibility seems however possible only with the car seat investigated in these studies.

This Chapter 8 starts by comparing the newly developed method with previous methods found in the literature. Then the discomfort-time-dependencies will be compared with those proposed in the standards ISO 2631 (1997) and BS 6841 (1987). The consequences of the subjective discomfort time-dependency results obtained on the standardized frequency weightings will be discussed. The possible mechanisms responsible of the production of SDTD will be presented. They involve neck muscle activity and the transmission of floor vibration to the upper-back, neck and head. From an understanding of these mechanisms, factors affecting SDTD will be discussed. Finally, possible means of predicting the discomfort time-dependency from the platform acceleration and the dynamic properties of the backrest will be presented.

8.2 COMPARISON BETWEEN THE NEWLY DEVELOPED METHOD AND PREVIOUS METHODS USED TO MEASURE COMFORT TIME-DEPENDENCY

8.2.1 Introduction

Chapter 2 showed that very little is known about the effects of the duration of exposure to vibration on discomfort. The rarity of studies can be explained by the lack of established methods to measure the evolution of discomfort with duration.

This section analysed the weaknesses of the previous methods used to measure discomfort time-dependency and describes how, from the identified weaknesses, the method presented in Chapter 3 was developed.

8.2.2 Analyses of the weaknesses of the previous methods

Section 2.2.1 of Chapter 2 has described the previous methods used to measure the evolution of discomfort with the vibration exposure duration. The magnitude estimation and matching methods required the exposure of two stimuli: a reference stimulus and a test stimulus. It is probable that the discomfort accumulated during exposure to the reference stimulus will affect the discomfort produced by the following reference vibration, and vice-a-versa. These methods are also not practical to measure the evolution of discomfort with prolonged exposure. A test stimulus of duration of 60 minutes will only give one point on the discomfort time-dependency at the 60th minute. All the other points between 0 and 60 minutes will still have to be measured requiring numerous stimuli of prolonged duration.

8.2.3 Development of the new method

To measure the evolution of discomfort with prolonged vibration exposure duration, the most suitable method will provide the continuous evaluation of discomfort with duration of one continuous stimulus. The method presented in Chapter 3 was developed according to this principle. The new method is derived from the matching method. The reference and the test stimuli are the same continuous stimulus. The reference is defined as being the first ten seconds of exposure. Then the 'matching' of the test stimulus is performed continuously. This procedure reduces the relative effects of the reference and test stimulus on each other. It also reduces critically the time needed to acquire a comfort time-dependency, as only one stimulus is needed.

8.2.4 Possible drawback of the method

This method may have a drawback. Because the discomfort experienced during the exposure of the reference motion may affect the judgement of the test motion, the reference was presented to the subjects only once, at the beginning of the session. With time, the reference might vary and subjects may adjust the magnitude of the stimulus to a level they judge comfortable. Therefore the magnitude of the acceleration may not represent the discomfort experienced during the reference motion but a magnitude representing a level of discomfort acceptable by the subjects. If this is the case, this method cannot be used if the effect of the magnitude of the excitation on the discomfort time-dependency is investigated. Subjects will tend to reduce the magnitude until they reach their acceptable level of discomfort. However in this study, this is not critical. The reference used by the subjects may be different from what was proposed. Subjects may use the 'acceptable level of discomfort' as their reference. But if duration affects comfort, subjects will have to adjust the magnitude of the excitation to reach their 'acceptable level of discomfort'. The effects of frequency, waveform and direction of excitation and also the effects of body support can still be investigated by this method.

8.2.5 Supporting information concerning the method

Supporting information concerning the new developed method has been given by testing its repeatability and by comparing the subjective results obtained with an alternative method (Griffin and Whitham, 1978). The results shown in Chapter 4 showed that the repeatability of the method is satisfactory. Also the subjective results obtained with the new developed method and the alternative method used (Griffin and Whitham, 1978) seem similar.

8.2.6 Conclusion

This method seems to be suitable and efficient to measure the subjective discomfort time-dependency (SDTD). Further tests of the method have been performed and more confidence in its accuracy was gained. More tests may be required to investigate if the method can measure accurately the effects of the magnitude of vibration on SDTD.

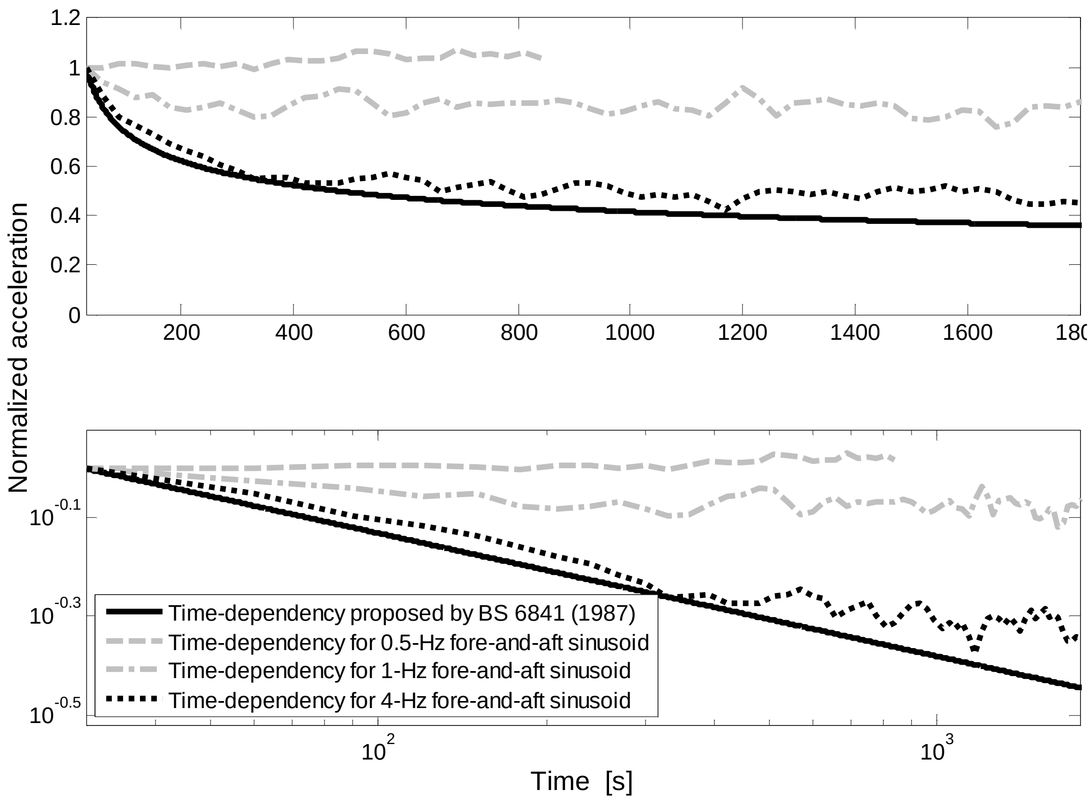


Figure 8.1 Comparison of the comfort time-dependency proposed by BS 6841 (1987) with the measured comfort time-dependency at 0.5 Hz, 1 Hz and 4 Hz in the fore-and-aft direction (see Chapter 3).

8.3 COMPARISON OF DISCOMFORT TIME-DEPENDENCIES OBTAINED IN THESE STUDIES WITH THESE PROPOSED BY THE STANDARDS ISO 2631 (1997) AND BS 6841 (1987)

8.3.1 Introduction

The subjective discomfort time-dependencies (SDTD) obtained in Chapter 3 showed that SDTD depends on the frequency and direction of excitation. The time-dependencies proposed by the standards ISO 2631 (1997) and BS 6841 (1987) suggest that discomfort increased with duration exposure independently of the frequency and direction of the vibration.

This section compares the different discomfort time-dependencies obtained, with the one proposed by the standards ISO 2631 (1997) and BS 6841 (1987). Then the effects of duration on the frequency-weighted curves proposed by those standards will be discussed.

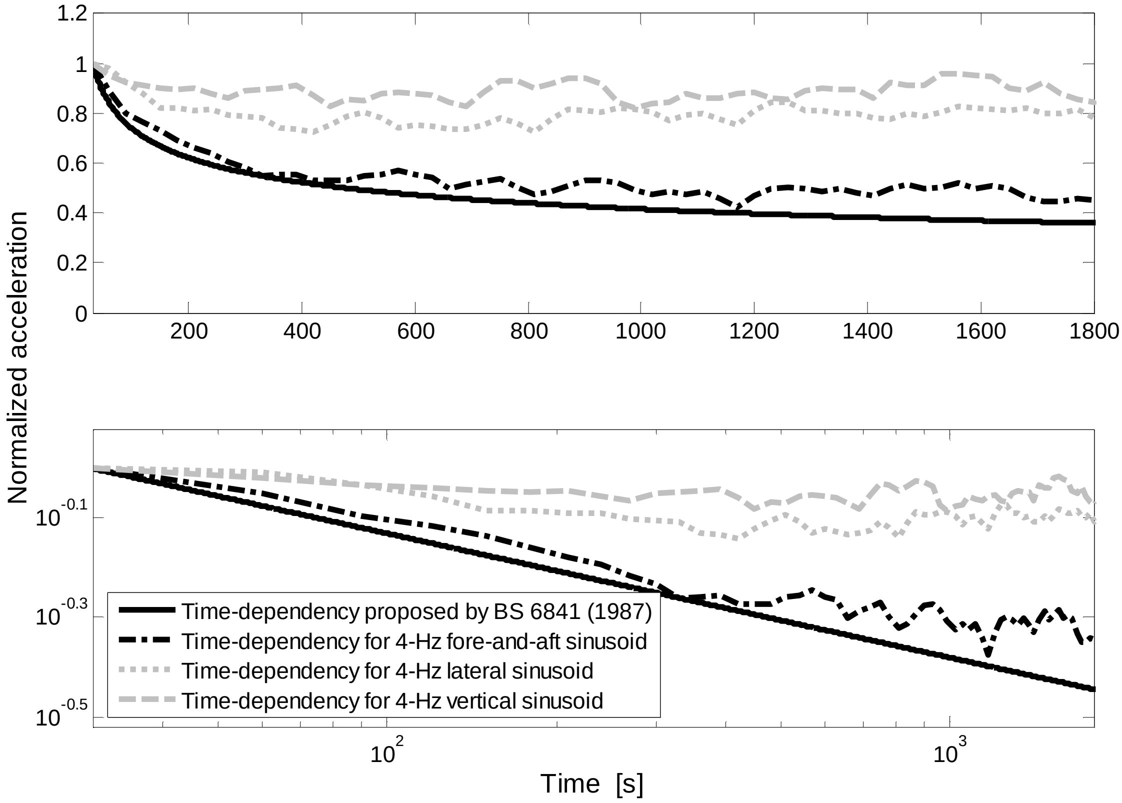


Figure 8.2 Comparison of the discomfort time-dependency proposed by standard BS 6841 (1987) with the measured discomfort time-dependency at 4 Hz in the fore-and-aft, lateral and vertical direction (see Chapter 3).

8.3.2 Comparison of discomfort time-dependencies

Both standards, ISO 2631 (1997) and BS 6841 (1987) used a time-dependency based on the root-mean-quad of the acceleration defined by $(a)^4 \times t$ = constant (with a the acceleration and t the duration of vibration exposure). More details of the discomfort time-dependencies proposed by the standards are presented in Chapter 2 (see Section 2.2.3, and Figures 2.10 and 2.11).

In BS 6841 (1987) the time dependency related to the r.m.q. is expressed according to the following relationship:

$$eVDV = \left[(1.4 \times a)^4 \times t\right]^{1/4} \qquad \text{equation 8.1}$$

where:

eVDV is the estimated vibration dose value (in m.s$^{-1.75}$);

a is the r.m.s. value (in m.s^{-2});

t is the duration (in s).

The discomfort time-dependencies presented in Figure 2.11 (and Figure3 page17 of BS 6841, 1987) assume that a constant value of eVDV represents a constant overall discomfort. Therefore the time-dependencies proposed by the standards are proportional to $t^{-1/4}$ (with *t* the exposure duration). They do not consider the possible effects of the vibration characteristics (*e.g.* frequency, direction). On the basis of this, discomfort will evolve with vibration exposure duration at the same rate, independently of the frequency or direction of excitation.

Figures 8.1 and 8.2 compare the discomfort time-dependencies obtained in Chapter 3 with the discomfort time dependency suggested by the standard BS 6841 (1987). To allow a better comparison of the measured discomfort time-dependencies measured and presented in Chapter 3 with the one proposed in the standard, the discomfort time-dependency suggested by equation 8.1 has been normalized.

Equation 8.1 gives the following expression of the comfort time-dependency:

$$K = eVDV = 1.4 \times a \times t^{1/4}$$

$$a = \frac{K}{1.4} \times t^{-1/4}$$

with :

a is the r.m.s. value (in m.s^{-2});

t is the duration (in s);

K is a constant representing a constant overall discomfort.

The normalization was performed similarly as conducted with the subjective study (see Chapter 3, Section 3.5.1) by dividing the discomfort time-dependency by the r.m.s. value of the acceleration after 10 seconds of exposure:

$$a_{normalized} = \frac{\frac{K}{1.4}}{\frac{K}{1.4} \times 10^{-1/4}} \times t^{-1/4}$$

which finally gives a normalized discomfort time-dependency proposed by the BS 6841 (1987) expressed by:

$$a_{normalized} = 10^{1/4} \times t^{-1/4}$$

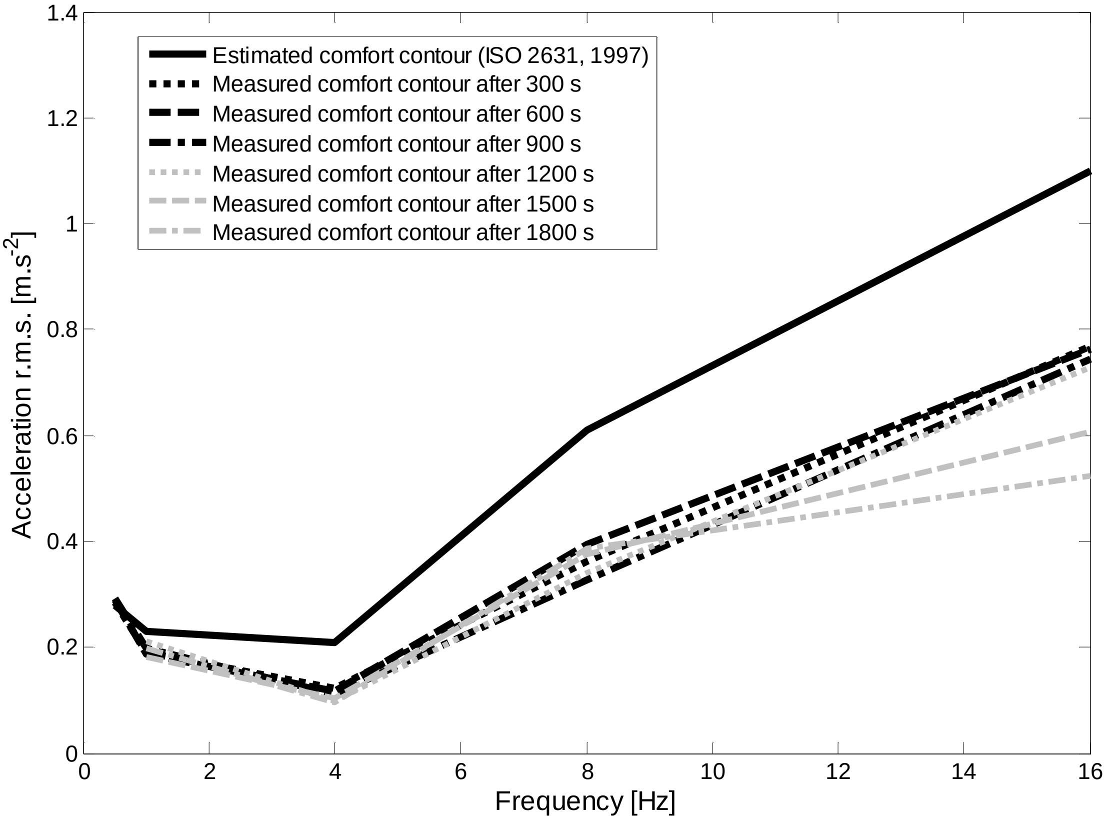


Figure 8.3 Effects of the vibration duration exposure on the estimated comfort contour (ISO 2631, 1997)

Figure 8.1 shows that the time-dependency proposed by BS 6841 (1987) fits well the discomfort time-dependency of the 4-Hz sinusoid. However, the discomfort time-dependencies caused by 0.5-Hz and 1-Hz sinusoids are not correctly estimated by the standard. Similarly, Figure 8.2 showed that the discomfort time-dependency proposed by the standard does not estimate correctly the time-dependencies caused by the 4-Hz lateral or vertical sinusoids.

This result suggests that the discomfort time-dependency proposed by the standards (either the BS 6841, 1987 or the ISO 2631, 1997) is not suitable to estimate the time-dependency of all types of vibration. The effects of frequency and direction on the discomfort time-dependency should be considered.

8.3.3 Effect of vibration exposure duration on the frequency-weighting curves

The effects of frequency and direction of excitation on the discomfort time-dependency affect also the frequency-weighting curves presented in ISO 2631 (1997) and BS 6841 (1987). These frequency-weighting curves consider the sensitivity of the human relative to the frequency but not to the duration of exposure. Figure 8.3 shows the effect of vibration duration exposure on the frequency-weighting curves. The estimated comfort contour presented in Figure 8.3 was calculated in Chapter 3, with the frequency-weighting curves, the multiplying factors and the backrest transmissibility (see Section 3.7.1). If the frequency of excitation did not have any effect on the discomfort time-dependency, all the time-dependencies presented after different durations of exposure should have followed similar trends to the time-dependency calculated with the frequency-weighting curves of ISO 2631 (1997). Figure 8.3 shows that this is not the case. To estimate accurately the comfort contour, frequency-weighting curves proposed by the standards should include the effects of the discomfort time-dependency on the frequency weightings.

8.3.4 Conclusion

The subjective discomfort time-dependencies obtained in Chapter 3 suggests that the time-dependency proposed in ISO 2631 (1997) and BS (1987) may not be accurate for all stimuli. The duration of vibration exposure affects the frequency-weighting curves proposed in those standards.

It could be suggested that the estimation of discomfort by the standards may be improved by investigating simultaneously the effects of frequency and duration on the comfort contours.

8.4 POSSIBLE MECHANISMS AND FACTORS AFFECTING THE DISCOMFORT TIME-DEPENDENCY

8.4.1 Introduction

The subjective studies presented in Chapter 3 showed that prolonged exposure to vibration caused discomfort, mainly at the neck. The discomfort time-dependency depended on the frequency and direction of the vibration and also on the body support. These results led to further studies that focused on the effects of whole-body vibration exposure on the neck muscles and head motions. Chapter 5 investigated the effect of the vibration frequency on neck muscle activity. Chapter 6 studied the transmission of vibration from the floor to the seat and to the head. The relationships between the subjective, physiological and biodynamic results have improved understanding of the mechanisms and factors responsible of the discomfort time-dependency.

8.4.2 Possible mechanisms of subejctive discomfort time-dependency

Neck muscle activity seems to be fundamental to the understanding of the mechanisms of the subjective discomfort time-dependency (SDTD). The ability of the muscle fibres to respond to vibration seems to reduce as the frequency of excitation increases. Previous studies on back muscles (Seidel, 1988; Robertson and Griffin, 1989) found that the muscle activity either led, or was in phase with, the platform acceleration at frequencies lower than about 2 Hz, then as the frequency increased, the EMG signals showed an increasing lag behind the acceleration (see Chapter 5, Figure 5.8). The results presented in Chapter 5 (Figure 5.14) showed that the part of the phasic neck muscle activity contained in the overall neck muscle activity was greatest at 1 Hz. Then, as the frequency of excitation increased muscle fibres produced less phasic activity and more tonic activity. It seems that for low frequency vibration, the muscle fibres can respond to the excitation by producing periodic contractions. As the frequency increases, the ability of the muscle fibres to respond to the vibration reduces and the muscle fibres tend to contract continuously. Time dependency seems to be linked with the dynamic properties of the muscle fibres. Chapter 3 showed that SDTD was greater with motions producing greater tonic activity and less phasic activity. This result suggest that when the muscle contracts periodically, producing greater phasic activity and less tonic activity, the muscle fibres exhibit less 'muscle fatigue', possibly because they are not exerting a constant tension. On the basis of this, head motions controlled mainly by phasic neck muscle activity should produce lower SDTD than head motions controlled by tonic neck muscle activity.

SDTD may be directly related to the magnitude of the tonic activity. The contraction of the muscle fibres may increase with increasing tonic activity, producing greater 'muscle fatigue' and therefore generating greater discomfort time-dependency. However this study could not investigate this as the calculated normalized tonic activity may not have represented accurately its absolute magnitude. As presented in Chapter 5 (Section 5.6.8), the phasic and tonic activity were normalized relative to the overall neck muscle activity. Because, the overall neck muscle activity was more or less constant with frequency, it was assumed that the normalized phasic and tonic activities were more or less proportional to their absolute values. It was also discussed that the process used to normalized the EMG signal (maximum voluntary contraction, MVC) might not have been enough refined to measure small differences between the overall EMG produced by different frequencies. A difference in the overall EMG between frequencies implies that the normalized and absolute values of the tonic activity are no longer proportional.

8.4.3 Factors affecting subjective discomfort time dependency

Section 8.4.2 suggests that the type of neck muscle response to whole-body vibration exposure may be related to subjective discomfort time-dependency (SDTD) and that the response of the neck is greatly dependent on the frequency of excitation. Therefore, the frequency of excitation is probably one of the most critical factors affecting time dependency.

Chapter 3 suggested that the direction of excitation and the body support / restraint may also affect SDTD. It has been suggested in Chapter 3 that different directions of excitation, due to the backrest of the seat, offer different body supports / restraints. The backrest restrains the upper body to move with fore-and-aft excitation. The trunk has better opportunities to attenuate the vibration transmitted to the head in the lateral and vertical direction. A study by Paddan and Griffin (1988) showed that vibration is more easily transmitted from the seat-pan to the head with fore-and-aft excitation than with lateral or vertical excitation (for most of the frequency range studied: 0.5 Hz to 16 Hz). Due to the backrest, the trunk may not be able to reduce the load put on the neck muscles during fore-and-aft vibration exposure. This could explain why fore-and-aft excitation tended to produce greater SDTD. Using a 4-points harness during exposure to 1-Hz lateral sinusoidal excitation produced greater SDTD. This tends to confirm that restricting the trunk so that it moves with the seat reduces its ability to attenuate vibration transmitted to the head. The effect of body restraint on SDTD may depend on the frequency of excitation. Section 8.4.2 suggested that the ability of the muscle fibres to respond to the excitation decreases with increasing frequency. It is possible that the ability of the trunk to attenuate the vibration transmitted to the head also reduces with the increase of tonic activity. A different effect on SDTD with the 4-point harness might be expected with a higher frequency of excitation. The fore-and-aft excitation produced a greater SDTD than lateral and vertical excitation only at 1 Hz and 4 Hz. No significant differences were found at 8 Hz or 16 Hz (see Chapter 3, Section 3.7.7). It may be suggested that due to the dynamic property of the muscle fibres, the effect of body support / restraint on SDTD may be attenuated as the frequency of excitation increases.

Another factor may affect SDTD. The magnitude of excitation was not investigated in these studies because it was assumed that the other variables chosen (frequency, waveform, direction, body support) would be more critical to understanding the mechanisms of time-dependency. Nevertheless, the vibration magnitude may also affect SDTD. As hypothesized for the body support / restraint, the effect of magnitude may depend on the frequency of the excitation. Section 8.4.2 suggested that head motions controlled by phasic activity may produce lower SDTD than head motion controlled by tonic neck muscle activity. It was also shown that with increasing frequency of excitation the part of the phasic activity in the overall muscle activity reduces, whereas the part of the tonic activity increases. On this basis it could be hypothesized that the magnitude of vibration may have greater effects on discomfort time-dependency at high frequency (where the muscle fibres are contracted continuously to control the head motion) than at lower frequencies (where the muscle fibres are not exerting a constant tension and therefore exhibit lower SDTD).

8.4.4 Conclusion

It seems that subjective discomfort time dependency (SDTD) may be related with the type of neck muscle activity produced to respond to the excitation. Head motions controlled mainly by tonic activity seem to generate more neck 'muscle fatigue' than head motions controlled by phasic activity. The parts of phasic and tonic activity in the overall neck muscle activity depend mainly on the frequency. The frequency of excitation is therefore a primary factor affecting SDTD. The body support / restraint and the vibration magnitude may also affect SDTD. But the effects of these factors may depend on the frequency of excitation.

8.5 PREDICTING THE DISCOMFORT TIME-DEPENDENCY

8.5.1 Introduction

Some mechanisms and factors affecting the subjective discomfort time dependencies (SDTD) were presented in Section 8.4. From these understandings a model predicting SDTD may be developed.

From an engineering point of view, it is interesting to be able to estimate SDTD from a physical measure that includes all the 'adjustable' parameters that may affect SDTD (e.g. vibration input, backrest transmissibility). It is even more interesting to be able to predict the physical measure that estimates SDTD. The engineer can adjust the various parameters until an optimized discomfort time-dependency is reached.

This section investigates the possible means to estimate SDTD from the acceleration at the floor and the dynamic properties of the backrest.

8.5.2 Possible models estimating subjective discomfort time-dependency

Figure 8.4 presents two kinds of model that may estimate subjective discomfort time-dependency (SDTD). 'Model A' may provide a rough estimation of the SDTD around the resonances observed in the floor-to-head transmissibility. 'Model B' should be considered with caution. This model was developed mainly on assumptions made from the observations of the relationships between the subjective, physiological and biodynamic results. Most of these assumptions were not tested. 'Model B' should therefore be considered rather as a set of hypotheses to be tested in further studies than the synthesis of all the results obtained in this thesis.

8.5.3 Model A

Model A suggests that subjective discomfort time-dependency (SDTD) may be estimated from a comparison between the predicted types of head motion (obtained with the predicted mode shapes) with the types of head motions identified in Chapter 7 and associated with different SDTD.

Figure 8.4 shows that SDTD may be estimated around the resonances of the floor-to-head transmissibility in two steps.

8.5.3.1 Step A1: Predicting the mode shapes (i.e., type of head motion)

Mode shapes are calculated from the three degree-of-freedom lumped parameter model described in Chapter 7 (see Figure 7.5) without the damping parameters. Chapter 6 suggested that the head and neck dynamic parameters may be accurate within 25%. The accuracy may be improved if subjects adopt similar postures within the different seats investigated. Chapter 6 also showed that the backrest transmissibility can provide an accurate estimation of the dynamic stiffness representing the dynamic stiffness of the backrest and upper-back tissues of the subject (i.e., parameter k_1 of the model described in Chapter 7, Figure 7.5). The damping of the backrest and the upper-back tissues of the subject (i.e., parameter c_1 of the model described in Chapter 7, Figure 7.5) cannot be estimated accurately with the damping of the backrest (see Chapter 7, Figure 7.15). Because the mode shapes are calculated without damping, an estimation of the type of head motion may still be possible if the dynamic stiffness of the backrest is known.

8.5.3.2 Step A2: Comparing the predicted types of head motion with the types of head motions identified in Chapter 7

Chapter 7 showed that the model optimized with the measured floor-to-head transmissibility provided three types of head motion at the resonances. By investigating the relationship between the calculated mode shapes and the subjective discomfort time-dependency (SDTD) obtained around the frequency of resonances (see Chapter 3), each type of head motion was associated with a different SDTD:

- Type of head motion number 1: ‘Head and neck are moving in phase’. This type of head motion presents a low SDTD.
- Type of head motion number 2: ‘Head and neck are moving in phase but the head motion is much greater then the neck motion’. This type of head motion presents a medium / high SDTD.

- Type of head motion number 3: ‘Head and neck are moving out-of-phase’. This type of head motion presents a high SDTD.

Therefore the predicted mode shapes corresponding to predicted types of head motions can be compared with the three identified types of head motion (number 1, 2 and 3) and the discomfort time-dependencies around the frequencies of resonance of the floor-to-head transmissibility can be estimated.

8.5.4 Model B

It will be recalled that Model B was constructed from assumptions derived from the study of the relationships between the subjective, physiological, and biodynamic results. Most of these assumptions have not been tested in this thesis. Model B should be considered as a set of hypotheses that may be investigated in further studies.

Model B suggests that subjective discomfort time-dependency (SDTD) may be estimated from the phase and modulus of the backrest-to-head transmissibility through the neck muscle activity. This model was developed from engineering considerations. The model should provide a useful tool if SDTD may be estimated from physical parameters that the engineer may control. On this basis, the floor vibration and the backrest properties were chosen as inputs of this model.

Figure 8.4 shows how Model B may estimate SDTD in four steps.

8.5.4.1 Step B1: Predicting the floor-to-head transmissibility from the backrest dynamic properties and the input vibration of the floor.

Chapter 7 showed that the three degree-of-freedom lumped parameter model could fit accurately the floor-to-head transmissibility once its parameters have been optimized. It is probable that the parameters of the model will require a new optimization for each new seat. Chapter 7 investigated whether the dynamic parameters, corresponding to the dynamic properties of the backrest and upper-back tissues of the subject (i.e., parameters k_1 *and* c_1 of the model described in Chapter 7, Figure 7.5), can be estimated from the backrest transmissibility. The results showed that only the dynamic stiffness of the backrest can be used, the damping does not represent the damping required by the model.

The biodynamic model requires more development to predict accurately the floor-to-head transmissibility for any seat. Therefore step B1 of Model B is not yet validated.

8.5.4.2 Step B2: Calculating the backrest-to-head transmissibility from the floor-to-head transmissibility and the backrest transmissibility.

The backrest-to-head transmissibility is more suitable than the floor-to-head transmissibility to represent the head motions transmitted through the neck. This allows the involvement of the neck muscles to be better estimated.

Chapter 7 (Figure 7.14) showed that the backrest-to-head transmissibility can be well predicted from the measured floor-to-head transmissibility and the backrest transmissibility.

8.5.4.3 Step B3: Determining from the assumed dynamic response of the muscle fibres and the phase of the backrest-to-head transmissibility, three zones assumed to represent different subjective discomfort time-dependencies

It was assumed that the head and neck motions can be estimated from the backrest-to-head transmissibility (if the input vibration at the backrest is known or predicted).

Chapter 6 showed that the relationship between the subjective discomfort time-dependency (SDTD) and the head motions relative to the upper-back (backrest-to-head transmissibility) cannot be understood without considering neck muscle activity. Chapter 5 suggested that head motions controlled mainly by phasic neck muscle activity produced less SDTD than head motions controlled mainly by tonic neck muscle activity. Chapter 5 also showed that the normalized phasic neck muscle activity and the normalized tonic neck muscle activity respectively decreased and increased with increasing frequency of excitation (from 1 Hz to 16 Hz). From these results, it was suggested that head motions mainly controlled by phasic activity arise from low frequency vibration. Head motions controlled mainly by tonic activity arise from high frequency vibration. An intermediate frequency range, where head motions are controlled by both phasic and tonic neck muscle activity was also suggested. This step, B3 of Model B, tends to estimate three frequency ranges, called zone 1, zone 2, and zone 3. Each zone corresponds to a different type of SDTD zone 1 can be associated with a low SDTD (because in this zone head motions are controlled mainly by phasic activity), zone 2 can be associated with an intermediate SDTD (because in this zone head motions are controlled by both phasic and tonic activity) and zone 3 can be associated with a high SDTD (because in this zone head motions are controlled mainly by tonic activity).

It may be suggested that head motions that lead, or are in phase with, the backrest acceleration may be controlled mainly by phasic activity. The boundary of zone 1 could be delimited by the frequency at which the head motions start to present a phase lag relative to the backrest acceleration. Zone 1 may be associated with a low SDTD because most of the muscle fibres can relax during a cycle.

The boundary between the second and third zone is more difficult to determine. Previous studies (Freund, 1983; Seidel *et al.,* 1986; Seidel, 1988) suggested that at frequencies greater than 16 Hz the muscle fibres are no longer able to produce phasic activity and therefore head motions at such higher frequencies would be controlled entirely by tonic activity. The second zone may be considered as causing an intermediate SDTD (because some muscle fibres can relax during a cycle), and the third zone as causing a greater SDTD (because all muscle fibres will be contracted continuously).

At this stage, subjective discomfort time-dependency cannot yet be estimated as the amounts of phasic and tonic activity have not been estimated. The determination of the three zones was performed to estimate the effects of the magnitude of the head motions on the SDTD.

8.5.4.4 Step B4: Determining the effects of the magnitude of head motion on the subjective discomfort time-dependency for each of the three zones previously determined

The modulus of the backrest-to-head transmissibility represents the magnitude of the head motion relative to the upper-back if the input acceleration at the upper-back is known.

Step B4 is the most critical step in Model B because it is the last stage required to estimate the subjective discomfort time-dependency (SDTD). However most of the assumptions presented in this section were not tested by studies conducted in this thesis. The assumptions presented seem reasonable in view of the results obtained in these, and previous, studies (mentioned later in this section). These assumptions may be proposed as hypotheses for further studies investigating the effect of vibration magnitude on neck muscle activity and SDTD.

Tonic activity presents a state where the muscle fibres are exerting a constant tension. It seems reasonable to suggest that ‘muscle fatigue’ may increase with an increase of tonic activity and therefore produce greater SDTD. This assumption could not be tested, possibly because the normalization process used to normalize the neck muscle activity (i.e., the maximum voluntary contraction, MVC) might not have been precise enough to measure small differences in the overall muscle activity between the different frequencies of excitation investigated (see Section 8.4.2). It is therefore a first hypothesis that could be tested in a further study using a more suitable means of EMG normalization.

Step B4 of Model B tends to estimate the magnitude of the tonic activity from the magnitude of the head motions in each of the three zones previously determined.

In zone 1, the head motions are controlled mainly by phasic activity. An increase in the magnitude of the head motion might be compensated by an increase of phasic activity with the tonic activity not greatly affected. At 1 Hz, the seat-to-head transmissibility presented a resonance (see Chapter 6), whereas the subjective studies (Chapter 3) showed that SDTD was less at 1 Hz than at higher frequencies. Although it is a reasonable assumption, it was also not tested in these studies. This assumption could be used as another hypothesis in a further study.

In zone 2, head motions are controlled by both phasic and tonic activity. It is therefore difficult to estimate the effect of the magnitude of head motions on tonic activity as both phasic and tonic activity can increase with magnitude. Chapter 6 (Figure 6.7) showed that around the resonances (at about 4 Hz), as the magnitude of the random fore-and-aft motion increased, the peak and the resonance frequency decreased. The transmissibility and mechanical impedance of the body in previous studies show similar effects of the vibration magnitude on the frequency of resonance (e.g., Fairley and Griffin, 1989; Mansfield and Griffin, 2002). This may suggest a softening of the body as the excitation magnitude increase. Phasic activity might increase with increasing magnitude whereas the tonic activity could stay more or less constant. However it is still very unclear how magnitude of excitation may affect the discomfort time-dependency in this zone.

In zone 3, head motions are mainly controlled by tonic activity. It could be suggested that tonic activity tends to reduce the head motions. With this assumption, it is expected to have in zone 3 lower magnitudes of head motions than in zone 1 and 2. It is difficult to state the SDTD in this zone from the magnitude of the head motions. The magnitude of the head motion may be low because a high level of tonic activity is produced to control and reduce the head motion. It could be suggested that if the magnitude of head motions increases in zone 3, the tonic activity produced by the neck muscle reached its limit and greatest SDTD could be expected. This is another assumption that was not tested in these studies and could be used as another hypothesis for further research.

8.5.5 Conclusion

This section presented two possible models that may estimate the subjective discomfort time-dependency (SDTD). One model is based on the studies conducted in Chapter 3, 6, and 7. This model estimates SDTD by comparing the predicted mode shapes with the identified types of head motion associated with different type of discomfort time-dependencies. The second model explores the possible mechanisms that could lead to a prediction of SDTD. The second model offers different hypotheses, which may lead to a further understanding of the effect of vibration magnitude on SDTD.

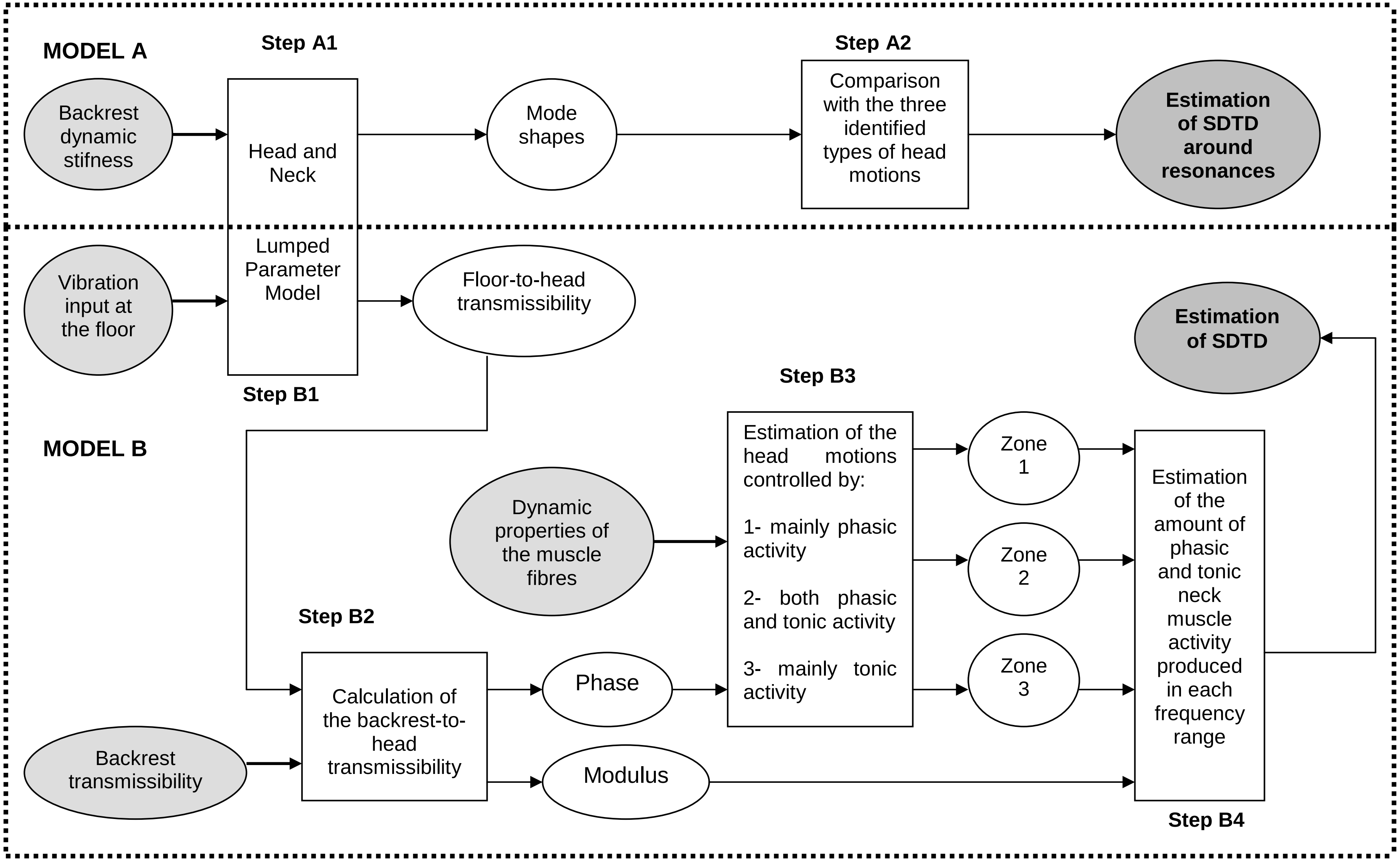
8.6 CONCLUSION

The work conducted in this thesis led to the development of a new method to evaluate the effects of vibration duration exposure on the subjective discomfort time-dependency (SDTD). Satisfying confidence in the method has been gained for this method to be used for further research.

The method provided results suggesting that the effects of frequency and direction of excitation on the discomfort time-dependency may affect the accuracy of the frequency-weighting curves and time-dependency curves proposed in ISO 2631 (1997) and BS 6841 (1987). It is suggested that the frequency-weighting and time-dependency curves should be studied together to take into account the effects of frequency and direction of excitation on the discomfort time-dependency.

One model using the mode shapes of a three degree-of-freedom lumped parameter model was presented as being able to estimate roughly the subjective discomfort time-dependency around the frequencies of resonance. A second model proposed a means to predict SDTD but mainly offers hypotheses to be investigated in further research.

Figure 8.4 Proposed models for estimating the subjective discomfort time-dependency (SDTD)



9 CONCLUSION

9.1 INTRODUCTION

As set out in Chapter 1, Section 1.2, this thesis had three main objectives:

- To develop a new method suitable to measure and compare the subjective discomfort time-dependencies produced by various vibratory stimuli.
- To investigate the effects of different vibration characteristics (frequency, waveform and direction) and body supports on the subjective discomfort time-dependency.
- To improve understanding of the mechanisms involved in the production of the subjective discomfort time-dependency experienced during prolonged exposure to vibration and to develop a model of the subjective discomfort time-dependency.

A method has been developed, as described in Chapter 3, Section 3.4. In Chapter 4, repeatability measurements and an alternative method have been used to provide further information on the method. These experiments showed encouraging results, which reinforce confidence in the method.

The effects of vibration exposure duration on discomfort and the location of discomfort were investigated with seated subjects exposed to different types of vibration inputs. The effects of frequency, waveform and direction of excitation and also body restraint on the subjective discomfort time-dependency were studied. All the results have been fully described in Chapter 3. Section 9.2.1 summarizes the main findings.

To increase understanding of the possible mechanisms involved in subjective discomfort time-dependency, neck muscle activity was measured during exposure to vibration at different frequencies. For modelling purposes, vibrations transmitted from the floor to the seat and to the head were measured. From these measurements a biodynamic model was developed and calibrated. All results have been fully described in Chapters 5, 6 and 7. Sections 9.2.2 and 9.2.3 summarize the main findings. Section 9.2.4 presents briefly the model of subjective discomfort time-dependency fully described in Chapter 8.

This final chapter starts by presenting the main findings obtained from the subjective, physiological and biodynamic studies conducted. Then some recommendations for further research are proposed. Finally this chapter describes the overall contribution to knowledge.

9.2 MAIN FINDINGS

9.2.1 Subjective studies

The measurement of the subjective discomfort time-dependency (SDTD) required a new method more suitable and efficient than the methods previously used. A new method was then developed and supporting information concerning the method have been provided.

With this new method, the effects of vibration frequency (from 0.5 Hz to 16 Hz), vibration waveform (sinusoidal, narrowband random, broadband random and shocks), direction of vibration (fore-and-aft, lateral and vertical) and body restraint on the discomfort time-dependency were investigated. The results showed that discomfort increased mainly during the first 15 minutes of exposure (except for 1-Hz lateral and 0.5-Hz fore-and-aft sinusoids). The waveform of excitation had almost no effect on the discomfort time-dependency. For most of the stimuli investigated, the fore-and-aft direction was found to cause more SDTD than lateral and vertical vibration (especially for 1-Hz and 4-Hz excitation). The vibration frequency was probably the most critical factor affecting the discomfort time-dependency. SDTD tended to be greater with increasing frequency of excitation.

For each discomfort time-dependency acquired, the corresponding body locations of discomfort were measured. Results showed that for most stimuli, discomfort was felt at the neck and lower-back. The control study showed that discomfort at the neck was more probably due to prolonged exposure to vibration, whereas discomfort at the lower-back was more probably due to prolonged static posture.

The subjective study suggested that the type / quantity of neck muscle activity produced during exposure to vibration may be responsible of the subjective discomfort time-dependency.

9.2.2 Physiological studies

Neck muscle activity was measured on seated subjects exposed for 10 minutes to fore-and-aft sinusoidal vibration (from 0.5 Hz to 16 Hz). The r.m.s. of the EMG, the phasic neck muscle activity (muscle activity arising as a result of periodic vibration) and the tonic neck muscle activity (muscle activity needed to respond to a static load) were processed from the raw SEMG signals. The results showed that duration and frequency had no effect on the r.m.s. of the neck muscle activity. Phasic and tonic activity were normalized relative to their corresponding r.m.s. EMG values. The duration of exposure had no effect of the normalized phasic and tonic activity, but vibration frequency was found to be critical. The normalized phasic and tonic activity decreased and increased, respectively, with increasing frequency.

The relationship between the subjective results and the physiological results suggested that head motions controlled by mainly phasic neck muscle activity produced lower SDTD than head motions controlled mainly by tonic neck muscle activity.

9.2.3 Biodynamic studies

The transmission of fore-and-aft vibration from the floor to the seat and to the head was investigated to allow the identification of the types of head motions causing the subjective discomfort time-dependency (SDTD). The backrest-to-head transmissibility was measured to represent head motions relative to the upper-back, which were expected to reflect the involvement of the neck muscles. The floor-to-head transmissibility and seat transmissibility were measured for modelling purposes.

Measurements of vibration transmissibility indicated that the seat backrest affected greatly the vibration transmitted from the floor to the head, whereas the seat-pan had almost no effect. Results also showed that the backrest-to-head transmissibility can be predicted by dividing the floor-to-head transmissibility by the backrest transmissibility.

A three degree-of-freedom lumped parameter model representing the upper-back, the neck and the head was designed and its parameters optimized from the measured floor-to-head transmissibility. The mode shapes calculated provided three types of head motion: ‘head and neck moving in phase’ (at 1.4 Hz), ‘head and neck moving in phase with a motion of the head much greater than the motion of the neck’ (at 3.5 Hz); ‘head and neck moving out-of-phase’ (at 6.9 Hz). From the SDTD measured around the resonance frequencies, each type of head motion (identified from the calculated mode shapes) was associated with a different SDTD: ‘head and neck moving in phase’ was associated with a low SDTD; ‘head and neck moving in phase with a motion of the head much greater than the motion of the neck’ was associated with a medium / high SDTD; ‘head and neck moving out-of-phase’ was associated with a high SDTD.

The relationship between the head and neck motions provided by the backrest-to-head transmissibility and the subjective discomfort time-dependency cannot be understood without consideration of the neck muscle activity. It was suggested that the phase and modulus of the backrest transmissibility may be used to estimate the phasic and tonic neck muscle activity and the corresponding SDTD. These suggestions were mainly based on hypotheses that were not tested in this thesis. These hypotheses are suggested for further research on time-dependency.

9.2.4 Model estimating subjective discomfort time-dependency

For engineering purposes, it was proposed to estimate the subjective discomfort time-dependency (SDTD) from the input floor vibration and the known backrest dynamic properties. Two models have been proposed. The first model is based on the prediction of the mode shapes, for any seat, from the input floor vibration and the known dynamic stiffness of the backrest. The second model is based on the prediction of the backrest-to-head transmissibility from the input floor vibration and the backrest transmissibility. This second model however rather suggests hypotheses that could be tested in further research than a verified process to estimate SDTD.

Measured and predicted transmissibilities showed that the mode shapes could be estimated for any seat from the developed lumped parameter model and known dynamic stiffness of the backrest. The predicted mode shapes give types of head motion that can be compared with the identified types of head motion that were associated with different type of SDTD. This comparison can lead to an estimation of the discomfort time-dependency around the resonance frequencies of the floor-to-head transmissibility.

The second model was developed in four steps. The first step was to predict the floor-to-head transmissibility from the input floor vibration and the backrest transmissibility. However, the lumped parameter model proposed still requires more development to predict accurately the floor-to-head transmissibility for any given seat. The second step was to predict the backrest-to-head transmissibility from the floor-to-head transmissibility and the backrest transmissibility. It has been shown that this was possible if the floor-to-head transmissibility is accurate. The third step tended to determine, from the phase of the backrest-to-head transmissibility, three frequency ranges: zone 1 where head motions are controlled mainly by phasic activity (and are associated with a low SDTD), zone 2 where head motions are controlled by both phasic and tonic activity (and are associated with intermediate SDTD) and zone 3 where head motions are mainly controlled by tonic activity (and are associated with a high SDTD). This assumes that the phase of the backrest-to-head transmissibility is predictive of the phasic neck muscle activity. This seems a reasonable assumption but requires further investigation. The fourth step of the model seeks to estimate the effects of the magnitude of the head motion (in each of the three defined zones) on the amount of phasic and tonic activity produced. The relationship between the magnitude of head motion and the magnitudes of phasic and tonic activity was not investigated in this thesis. Therefore the suggestions made in step 4 of this model should be further investigated and are proposed as hypotheses for future research.

9.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Research conducted in this thesis suggested that neck muscle activity is a mechanism responsible for subjective discomfort time-dependency (SDTD) during exposure to whole-body vibration. The effects of the frequency of excitation on the neck muscle activity have already improved understanding of the mechanisms causing the SDTD. It is suggested further knowledge of the relationship between the phasic activity and the phase of the backrest-to-head transmissibility and the relationship between the magnitude of head motions and the magnitudes of phasic and tonic activity should further improve the understanding of discomfort time-dependency.

It is also suggested that a biodynamic model may be used to estimate SDTD. The estimation of SDTD could be more accurate with an improved lumped parameter model of the head and neck. The accuracy of biodynamic model could be improved by measuring inter-subject variability in the head and neck dynamic parameters.

9.4 CONTRIBUTION TO KNOWLEDGE

This thesis proposes a new method developed especially to measure the evolution of discomfort with vibration exposure duration. Supporting information concerning the method has been given. This method could be used in further research on discomfort time-dependency.

The subjective studies showed that discomfort increased mainly during the first 15 minutes of exposure but at rates that depend on the frequency and direction of excitation. These results have critical impacts on the time-dependency and frequency-weighting curves proposed in current standards (ISO 2631, 1997 and BS 6841, 1987).

Understanding of the mechanisms responsible of the subjectife discomfort time-dependency has been improved through the measure of neck muscle activity. All the questions have not been yet answered but hypotheses, which may further improve the understanding, have been suggested.

The first steps of a model predicting the time-dependency were proposed. At the present time the model can produce an estimation of SDTD from the predicted type of head motion.

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APPENDIX 1 : Statistical analysis of comfort time-dependencies

The variable names are constructed according to the following schema:

- the first letter is the type of waveform: s for sinusoid, r for narrowband random et sh for shocks.
- the number following the first letter corresponds to the frequency
- the second letter corresponds to the direction of excitation, l for lateral, f for fore-and-aft and v for vertical.
- the last number correspond to the duration, 0 for starting magnitude, 1 for 10 minutes, 3 for 30 minutes, 6 for 60 minutes, 10 for 10 minutes, 30 for 30 minutes, 15 for 15 minutes.

For example the variable r16f30 represent the r.m.s. acceleration of a narrowband random stimulus centred at 16 Hz in the fore-and-aft direction at the 30^{th} minute of exposure.

1. Effects of the duration of vibration exposure on the comfort time dependency

Fore-and-aft stimuli:

Friedman tests

Ranks

	Mean Rank
s4f0	4,00
s4f1	2,92
s4f3	1,83
s4f6	1,25

Test Statistics[a]

N	12,000
Chi-Square	31,900
df	3,000
Asymp. Sig.	,000

a. Friedman Test

Ranks

	Mean Rank
s1f0	3,33
s1f1	2,33
s1f3	2,67
s1f6	1,67

Test Statistics[a]

N	12,000
Chi-Square	10,400
df	3,000
Asymp. Sig.	,015

a. Friedman Test

Ranks

	Mean Rank
r4f0	4,00
r4f1	2,50
r4f3	1,75
r4f6	1,75

Test Statistics[a]

N	12,000
Chi-Square	24,300
df	3,000
Asymp. Sig.	,000

a. Friedman Test

Ranks

	Mean Rank
r1f0	3,33
r1f1	2,75
r1f3	2,08
r1f6	1,83

Test Statistics[a]

N	12,000
Chi-Square	9,900
df	3,000
Asymp. Sig.	,019

a. Friedman Test

Ranks

	Mean Rank
shf0	3,58
shf1	2,58
shf3	1,75
shf6	2,08

Test Statistics[a]

N	12,000
Chi-Square	13,800
df	3,000
Asymp. Sig.	,003

a. Friedman Test

Ranks

	Mean Rank
r8f0	2,58
r8f10	1,58
r8f30	1,83

Test Statistics[a]

N	12,000
Chi-Square	6,500
df	2,000
Asymp. Sig.	,039

a. Friedman Test

Ranks

	Mean Rank
r16f0	2,83
r16f10	2,00
r16f30	1,17

Test Statistics[a]

N	12,000
Chi-Square	16,667
df	2,000
Asymp. Sig.	,000

a. Friedman Test

Wilcoxon tests

The numbers in these tables represents the asymptotic significance between normalized r.m.s. acceleration at the beginning of the session and at the 10^{th}, 15^{th}, 30^{th} and 60^{th} minute of exposure:

Fore-and-aft	after 10 mins	after 15 mins	after 30 mins	after 60 mins
Sinusoid 0.5 Hz		0.169		
Sinusoid 1 Hz	0.015		0.099	0.003
Sinusoid 4 Hz	0.002		0.002	0.002
Random 1 Hz	0.209		0.060	0.019
Random 4 Hz	0.002		0.002	0.002
Random 8 Hz	0.006		0.060	
Random 16 Hz	0.005		0.008	
Shock	0.028		0.004	0.002

Fore-and-aft	10 vs 30 mins	30 vs 60 mins
Sinusoid 0.5 Hz		
Sinusoid 1 Hz	0.480	0.117
Sinusoid 4 Hz	0.003	0.084
Random 1 Hz	0.158	0.695
Random 4 Hz	0.071	0.530
Random 8 Hz	0.388	
Random 16 Hz	0.034	
Shock	0.010	0.308

Lateral stimuli:

Friedman tests

Ranks

	Mean Rank
s4l0	3,58
s4l1	2,42
s4l3	2,33
s4l6	1,67

Test Statistics[a]

N	12,000
Chi-Square	13,700
df	3,000
Asymp. Sig.	,003

a. Friedman Test

Ranks

	Mean Rank
s1l0	2,42
s1l1	2,33
s1l3	2,92
s1l6	2,33

Test Statistics[a]

N	12,000
Chi-Square	1,700
df	3,000
Asymp. Sig.	,637

a. Friedman Test

Ranks

	Mean Rank
r4l0	3,08
r4l1	2,67
r4l3	2,25
r4l6	2,00

Test Statistics[a]

N	12,000
Chi-Square	12,900
df	3,000
Asymp. Sig.	,042

a. Friedman Test

Ranks

	Mean Rank
r1l0	3,50
r1l1	2,17
r1l3	2,25
r1l6	2,08

Test Statistics[a]

N	12,000
Chi-Square	9,700
df	3,000
Asymp. Sig.	,021

a. Friedman Test

Ranks

	Mean Rank
shl0	3,42
shl1	2,92
shl3	1,83
shl6	1,83

Test Statistics[a]

N	12,000
Chi-Square	13,700
df	3,000
Asymp. Sig.	,003

a. Friedman Test

Ranks

	Mean Rank
r8l0	2,67
r8l10	1,75
r8l30	1,58

Test Statistics[a]

N	12,000
Chi-Square	8,167
df	2,000
Asymp. Sig.	,017

a. Friedman Test

Ranks

	Mean Rank
r16l0	2,92
r16l10	1,58
r16l30	1,50

Test Statistics[a]

N	12,000
Chi-Square	15,167
df	2,000
Asymp. Sig.	,001

a. Friedman Test

Wilcoxon

Lateral	after 10 mins	after 15 mins	after 30 mins	after 60 mins
Sinusoid 1 Hz	0.638		0.388	1.000
Sinusoid 1 Hz with harness		0.042		
Sinusoid 4 Hz	0.008		0.071	0.012
Random 1 Hz	0.006		0.019	0.050
Random 4 Hz	0.638		0.099	0.012
Random 8 Hz	0.010		0.012	
Random 16 Hz	0.002		0.003	
Shock	0.099		0.004	0.012

Lateral	10 vs 30 mins	30 vs 60 mins
Sinusoid 1 Hz	0.638	0.099
Sinusoid 1 Hz with harness		
Sinusoid 4 Hz	1.000	0.071
Random 1 Hz	0.182	0.638
Random 4 Hz	0.433	0.433
Random 8 Hz	0.480	
Random 16 Hz	0.530	
Shock	0.004	1.000

Vertical stimuli:

Friedman tests

Ranks

	Mean Rank
s4v0	3,75
s4v1	2,83
s4v3	1,83
s4v6	1,58

Test Statistics[a]

N	12,000
Chi-Square	21,300
df	3,000
Asymp. Sig.	,000

a. Friedman Test

Ranks

	Mean Rank
s1v0	3,08
s1v1	2,50
s1v3	2,83
s1v6	1,58

Test Statistics[a]

N	12,000
Chi-Square	9,300
df	3,000
Asymp. Sig.	,026

a. Friedman Test

Ranks

	Mean Rank
r4v0	3,09
r4v1	2,36
r4v3	2,45
r4v6	2,09

Test Statistics[a]

N	11,000
Chi-Square	3,545
df	3,000
Asymp. Sig.	,315

a. Friedman Test

Ranks

	Mean Rank
r1v0	3,25
r1v2	2,08
r1v3	2,00
r1v6	2,67

Test Statistics[a]

N	12,000
Chi-Square	7,300
df	3,000
Asymp. Sig.	,043

a. Friedman Test

Ranks

	Mean Rank
shv0	3,75
shv1	2,25
shv3	2,08
shv6	1,92

Test Statistics[a]

N	12,000
Chi-Square	15,400
df	3,000
Asymp. Sig.	,002

a. Friedman Test

Ranks

	Mean Rank
r8v0	2,25
r8v10	1,92
r8v30	1,83

Test Statistics[a]

N	12,000
Chi-Square	1,167
df	2,000
Asymp. Sig.	,558

a. Friedman Test

Ranks

	Mean Rank
r16v0	2,67
r16v10	1,67
r16v30	1,67

Test Statistics[a]

N	12,000
Chi-Square	8,000
df	2,000
Asymp. Sig.	,018

a. Friedman Test

Wilcoxon

Vertical	after 10 mins	after 15 mins	after 30 mins	after 60 mins
Sinusoid 1 Hz	0.875		0.875	0.010
Sinusoid 4 Hz	0.006		0.034	0.003
Random 1 Hz	0.092		0.010	0.272
Random 16 Hz	0.005		0.019	
Shock	0.010		0.004	0.028

Vertical	10 vs 30 mins	30 vs 60 mins
Sinusoid 1 Hz	0.754	0.005
Sinusoid 4 Hz	0.071	0.084
Random 1 Hz	0.937	0.071
Random 16 Hz	0.754	
Shock	0.158	0.346

2. Effects of the direction of vibration on the comfort time dependency

Friedman tests

Ranks

	Mean Rank
s4f6	1,38
s4l6	2,00
s4v6	2,62

Test Statistics[a]

N	8,000
Chi-Square	6,250
df	2,000
Asymp. Sig.	,044

a. Friedman Test

Ranks

	Mean Rank
s1f6	1,50
s1l6	3,00
s1v6	1,50

Test Statistics[a]

N	8,000
Chi-Square	12,000
df	2,000
Asymp. Sig.	,002

a. Friedman Test

Ranks

	Mean Rank
r4f6	1,00
r4l6	2,29
r4v6	2,71

Test Statistics[a]

N	7,000
Chi-Square	11,143
df	2,000
Asymp. Sig.	,004

a. Friedman Test

Ranks

	Mean Rank
r1f6	2,57
r1v6	1,57
r1l6	1,86

Test Statistics[a]

N	7,000
Chi-Square	3,714
df	2,000
Asymp. Sig.	,156

a. Friedman Test

Ranks

	Mean Rank
r8l30	1,80
r8f30	1,70
r8v30	2,50

Test Statistics[a]

N	10,000
Chi-Square	3,800
df	2,000
Asymp. Sig.	,150

a. Friedman Test

Ranks

	Mean Rank
r16f30	2,00
r16l30	1,90
r16v30	2,10

Test Statistics[a]

N	10,000
Chi-Square	,200
df	2,000
Asymp. Sig.	,905

a. Friedman Test

Ranks

	Mean Rank
shf6	2,25
shl6	2,12
shv6	1,62

Test Statistics[a]

N	8,000
Chi-Square	1,750
df	2,000
Asymp. Sig.	,417

a. Friedman Test

Wilcoxon

	Lateral vs Fore-and-aft	Lateral vs Vertical	Fore-and-aft vs Vertical
Sinusoid 1 Hz	0.012	0.012	0.878
Sinusoid 4 Hz	0.048	0.327	0.007
Random 4 Hz	0.007	0.327	0.012

3. Effects of the waveform of vibration on the comfort time dependency

Friedman

Ranks

	Mean Rank
s1l6	2,57
r1l6	1,71
shl6	1,71

Test Statistics[a]

N	7,000
Chi-Square	9,429
df	2,000
Asymp. Sig.	,048

a. Friedman Test

Ranks

	Mean Rank
s1f6	2,25
r1f6	2,17
shf6	1,58

Test Statistics[a]

N	12,000
Chi-Square	3,167
df	2,000
Asymp. Sig.	,205

a. Friedman Test

Ranks

	Mean Rank
s1v6	2,60
r1v6	1,90
shv6	1,50

Test Statistics[a]

N	10,000
Chi-Square	6,200
df	2,000
Asymp. Sig.	,045

a. Friedman Test

Wilcoxon

	1 Hz			4 Hz
	Sinusoid vs Random	Sinusoid vs Shock	Random vs Shock	Sinusoid vs Random
Lateral	0.044	0.025	0.333	0.123
Fore-and-aft	0.814	0.182	0.117	0.433
Vertical	0.093	0.087	0.044	0.386

4. Effects of the frequency of vibration on the comfort time dependency

Friedman tests

Ranks

	Mean Rank
r4f3	2,25
r1f3	3,50
r8f30	2,42
r16f30	1,83

Test Statistics[a]

N	6,000
Chi-Square	10,542
df	3,000
Asymp. Sig.	,0136

a. Friedman Test

Ranks

	Mean Rank
r4l3	3,14
r1l3	2,71
r8l30	2,43
r16l30	1,71

Test Statistics[a]

N	7,000
Chi-Square	4,543
df	3,000
Asymp. Sig.	,208

a. Friedman Test

Ranks

	Mean Rank
r4v3	3,75
r1v3	2,00
r8v30	2,75
r16v30	1,50

Test Statistics[a]

N	8,000
Chi-Square	13,800
df	3,000
Asymp. Sig.	,003

a. Friedman Test

Wilcoxon

	Sinusoid			Random					
	0.5 Hz vs 1 Hz	0.5 Hz vs 4 Hz	1 Hz vs 4 Hz	1 Hz vs 4 Hz	1 Hz vs 8 Hz	1 Hz vs 16 Hz	4 Hz vs 8 Hz	4 Hz vs 16 Hz	8 Hz vs 16 Hz
Lateral			0.006	1.000	0.176	0.176	0.310	1.00	0.158
Fore-and-aft	0.005	0.005	0.002	0.002	0.043	0.045	0.600	0.116	0.308
Vertical			0.272	0.695	0.327	0.263	0.093	0.050	0.023

5. Effects of the body restrain on the comfort time dependency

	Lateral 1 Hz sinusoid with harness
Lateral 1 Hz sinusoid without harness	0.039
Fore-and-aft 1 Hz	0.799

APPENDIX 2 : Statistical analysis Location of discomfort

The variable‘s names are constructed according to the following schema:

- first letter represents the direction of the vibration
- the second letter represents the waveform
- then the number represent the frequency
- the remaining letter represent the location: neck, shou:shoulder, uppbad;upperback, midba:middle back, lowba: lower back, butt: buttocks, leg: legs, belly: belly.

1. Location of most discomfort

Lateral stimuli

Friedman

Ranks

	Mean Rank
ls4neck	4,96
ls4shou	2,88
ls4uppba	3,42
ls4midba	4,04
ls4lowba	5,04
ls4butt	4,00
ls4leg	3,67

Test Statistics[a]

N	12,000
Chi-Square	15,536
df	6,000
Asymp. Sig.	,016

a. Friedman Test

Ranks

	Mean Rank
ls1neck	5,29
ls1shou	3,71
ls1uppba	3,42
ls1midba	3,67
ls1lowba	5,08
ls1butt	3,38
ls1leg	3,46

Test Statistics[a]

N	12,000
Chi-Square	16,288
df	6,000
Asymp. Sig.	,012

a. Friedman Test

Ranks

	Mean Rank
lr4neck	3,83
lr4shou	3,33
lr4uppba	3,62
lr4midba	3,83
lr4lowba	5,42
lr4butt	4,42
lr4leg	3,54

Test Statistics[a]

N	12,000
Chi-Square	19,257
df	6,000
Asymp. Sig.	,004

a. Friedman Test

Ranks

	Mean Rank
lr1neck	4,42
lr1shou	3,25
lr1uppba	3,25
lr1midba	4,25
lr1lowba	5,25
lr1butt	3,79
lr1leg	3,79

Test Statistics[a]

N	12,000
Chi-Square	19,125
df	6,000
Asymp. Sig.	,004

a. Friedman Test

Ranks

	Mean Rank
lshneck	4,88
lshshou	3,58
lshuppba	3,62
lshmidba	4,21
lshlowba	5,04
lshbutt	3,33
lshleg	3,33

Test Statistics[a]

N	12,000
Chi-Square	18,329
df	6,000
Asymp. Sig.	,005

a. Friedman Test

Ranks

	Mean Rank
lr8head	4,17
lr8neck	5,29
lr8uppba	4,54
lr8midba	3,88
lr8lowba	5,17
lr8butt	4,21
lr8leg	4,50
lr8belly	4,25

Test Statistics[a]

N	12,000
Chi-Square	10,521
df	7,000
Asymp. Sig.	,161

a. Friedman Test

Ranks

	Mean Rank
lr16head	4,04
lr16neck	5,08
lr16uppba	4,96
lr16midba	4,54
lr16lowba	4,83
lr16butt	4,42
lr16leg	4,38
lr16belly	3,75

Test Statistics[a]

N	12,000
Chi-Square	7,558
df	7,000
Asymp. Sig.	,373

a. Friedman Test

With harness:

Ranks

	Mean Rank
ls1hhead	4,12
ls1hneck	6,42
ls1hshou	3,75
ls1huppba	4,04
ls1hmidba	3,75
ls1hlowba	5,04
ls1hbutt	4,12
ls1hleg	4,75

Test Statistics[a]

N	12,000
Chi-Square	25,578
df	7,000
Asymp. Sig.	,001

a. Friedman Test

Wilcoxon: Asymptotic significance

Lateral sinusoid 1 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.149	0.096	0.048	0.398	0.016	0.027
Shoulders			0.414	0.680	0.161	0.336	0.496
Upper-back				0.705	0.024	0.705	1.000
Middle-back					0.084	0.414	0.785
Lower-back						0.031	0.087
Buttocks							0.665

Lateral sinusoid 4 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.016	0.046	0.086	1.000	0.202	0.046
Shoulders			0.157	0.046	0.016	0.063	0.102
Upper-back				0.414	0.041	0.157	0.480
Middle-back					0.142	0.516	1.000
Lower-back						0.096	0.540
Buttocks							0.063

Lateral random 1 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.046	0.046	0.680	0.109	0.739	0.705
Shoulders			1.000	0.109	0.014	0.180	0.180
Upper-back				0.109	0.014	0.180	0.180
Middle-back					0.380	0.257	0.180
Lower-back						0.034	0.034
Buttocks							1.000

Lateral random 4 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.180	0.785	1.000	0.026	0.257	0.317
Shoulders			0.317	0.180	0.014	0.102	0.317
Upper-back				0.785	0.016	0.194	0.655
Middle-back					0.062	0.269	0.414
Lower-back						0.167	0.016
Buttocks							0.102

Lateral Shock	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.034	0.084	0.234	1.000	0.038	0.038
Shoulders			1.000	0.317	0.034	0.317	0.317
Upper-back				0.317	0.034	0.317	0.317
Middle-back					0.248	0.083	0.083
Lower-back						0.020	0.020
Buttocks							1.000

Lateral 1 Hz with harness	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Head	0.031	0.317	1.0	0.317	0.480	1.0	0.705
Neck		0.010	0.008	0.010	0.070	0.031	0.047
Shoulders			0.317	1.0	0.046	0.317	0.083
Upper-back				0.317	0.480	1.0	0.705
Middle-back					0.046	0.317	0.083
Lower-back						0.480	0.705
Buttocks							0.705

Fore-and-aft stimuli

Friedman

Ranks

	Mean Rank
fs4neck	5,21
fs4shou	3,12
fs4uppba	4,00
fs4midba	4,29
fs4lowba	4,58
fs4butt	3,38
fs4leg	3,42

Test Statistics[a]

N	12,000
Chi-Square	16,939
df	6,000
Asymp. Sig.	,010

a. Friedman Test

Ranks

	Mean Rank
fs1neck	5,62
fs1shou	3,25
fs1uppba	3,54
fs1midba	3,25
fs1lowba	5,04
fs1butt	3,79
fs1leg	3,50

Test Statistics[a]

N	12,000
Chi-Square	29,845
df	6,000
Asymp. Sig.	,000

a. Friedman Test

Ranks

	Mean Rank
fr4neck	4,96
fr4shou	3,50
fr4uppba	3,50
fr4midba	4,38
fr4lowba	4,38
fr4butt	3,79
fr4leg	3,50

Test Statistics[a]

N	12,000
Chi-Square	14,057
df	6,000
Asymp. Sig.	,029

a. Friedman Test

Ranks

	Mean Rank
fr1neck	5,58
fr1shou	3,46
fr1uppba	3,75
fr1midba	3,71
fr1lowba	4,58
fr1butt	3,46
fr1leg	3,46

Test Statistics[a]

N	12,000
Chi-Square	27,784
df	6,000
Asymp. Sig.	,000

a. Friedman Test

Ranks

	Mean Rank
fshneck	5,04
fshshou	3,88
fshuppba	3,88
fshmidba	3,58
fshlowba	4,46
fshbutt	3,58
fshleg	3,58

Test Statistics[a]

N	12,000
Chi-Square	19,000
df	6,000
Asymp. Sig.	,004

a. Friedman Test

Ranks

	Mean Rank
fr8head	4,00
fr8neck	5,04
fr8uppba	4,29
fr8midba	4,00
fr8lowba	5,75
fr8butt	4,29
fr8leg	4,33
fr8belly	4,29

Test Statistics[a]

N	12,000
Chi-Square	16,893
df	7,000
Asymp. Sig.	,018

a. Friedman Test

Ranks

	Mean Rank
fr16head	4,46
fr16neck	4,79
fr16uppba	4,46
fr16midba	4,46
fr16lowba	4,79
fr16butt	4,46
fr16leg	4,46
fr16belly	4,12

Test Statistics[a]

N	12,000
Chi-Square	2,729
df	7,000
Asymp. Sig.	,909

a. Friedman Test

Ranks

	Mean Rank
fs05head	4,67
fs05neck	5,33
fs05shou	4,04
fs05uppba	4,33
fs05midba	4,38
fs05lowba	4,71
fs05but	4,17
fs05leg	4,38

Test Statistics[a]

N	12,000
Chi-Square	5,214
df	7,000
Asymp. Sig.	,634

a. Friedman Test

Wilcoxon : Asymptotic significance

Fore-and-aft sinusoid 1 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.008	0.014	0.008	0.829	0.033	0.008
Shoulders			0.317	1.000	0.026	0.177	0.317
Upper-back				0.317	0.041	0.317	1.000
Middle-back					0.026	0.157	0.317
Lower-back						0.038	0.047
Buttocks							0.564

Fore-and-aft sinusoid 4 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.015	0.084	0.238	0.470	0.030	0.024
Shoulders			0.102	0.059	0.038	0.317	0.317
Upper-back				0.783	0.453	0.257	0.257
Middle-back					0.603	0.046	0.102
Lower-back						0.084	0.063
Buttocks							1.000

Fore-and-aft random 1 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.015	0.023	0.015	0.083	0.015	0.015
Shoulders			0.317	0.317	0.046	1.000	1.000
Upper-back				1.000	0.180	0.317	0.317
Middle-back					0.083	0.317	0.317
Lower-back						0.046	0.046
Buttocks							1.000

Fore-and-aft random 4 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.034	0.034	0.317	0.885	0.096	0.034
Shoulders			1.000	0.083	0.102	0.317	1.000
Upper-back				0.083	0.102	0.317	1.000
Middle-back					0.516	0.317	0.083
Lower-back						0.194	0.102
Buttocks							0.317

Fore-and-aft random 8 Hz	Neck	Upper-back	Middle-back	Lower-back	Buttocks	Legs	Belly
Head	0.102	0.317	1.000	0.034	0.317	0.317	0.317
Neck		0.048	0.102	0.608	0.257	0.257	0.257
Upper-back			0.317	0.096	1.000	1.000	1.000
Middle-back				0.034	0.317	0.317	0.317
Lower-back					0.025	0.050	0.025
Buttocks						1.000	1.000
Legs							1.000

Fore-and-aft Shock	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.059	0.059	0.038	0.317	0.038	0.038
Shoulders			1.000	0.317	0.157	0.317	0.317
Upper-back				0.317	0.157	0.317	0.317
Middle-back					0.102	1.000	1.000
Lower-back						0.102	0.102
Buttocks							1.000

Vertical

Firedman

Ranks

	Mean Rank
vs4neck	5,21
vs4shou	3,75
vs4uppba	4,04
vs4midba	3,75
vs4lowba	4,04
vs4butt	3,75
vs4leg	3,46

Test Statistics[a]

N	12,000
Chi-Square	15,484
df	6,000
Asymp. Sig.	,017

a. Friedman Test

Ranks

	Mean Rank
vs1neck	4,42
vs1shou	3,83
vs1uppba	3,83
vs1midba	4,12
vs1lowba	4,12
vs1butt	3,83
vs1leg	3,83

Test Statistics[a]

N	12,000
Chi-Square	6,500
df	6,000
Asymp. Sig.	,370

a. Friedman Test

Ranks

	Mean Rank
vr4neck	4,21
vr4shou	3,67
vr4uppba	3,96
vr4midba	3,38
vr4lowba	4,67
vr4butt	4,21
vr4leg	3,92

Test Statistics[a]

N	12,000
Chi-Square	7,595
df	6,000
Asymp. Sig.	,269

a. Friedman Test

Ranks

	Mean Rank
vr1neck	4,50
vr1shou	3,71
vr1uppba	3,42
vr1midba	4,08
vr1lowba	4,58
vr1butt	3,79
vr1leg	3,92

Test Statistics[a]

N	12,000
Chi-Square	7,567
df	6,000
Asymp. Sig.	,272

a. Friedman Test

Ranks

	Mean Rank
vshneck	4,38
vshshou	3,75
vshuppba	3,50
vshmidba	4,08
vshlowba	4,21
vshbutt	4,17
vshleg	3,92

Test Statistics[a]

N	12,000
Chi-Square	5,254
df	6,000
Asymp. Sig.	,512

a. Friedman Test

Ranks

	Mean Rank
vr8head	4,71
vr8neck	5,04
vr8uppba	4,33
vr8midba	4,33
vr8lowba	5,21
vr8butt	4,08
vr8leg	3,96
vr8belly	4,33

Test Statistics[a]

N	12,000
Chi-Square	6,167
df	7,000
Asymp. Sig.	,520

a. Friedman Test

Ranks

	Mean Rank
vr16head	5,71
vr16neck	5,17
vr16uppba	3,79
vr16midba	3,88
vr16lowba	5,38
vr16butt	4,46
vr16leg	3,79
vr16belly	3,83

Test Statistics[a]

N	12,000
Chi-Square	17,520
df	7,000
Asymp. Sig.	,014

a. Friedman Test

Wilcoxon: Asymptotic significance

Vertical sinusoid 4 Hz	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		0.025	0.059	0.058	0.059	0.034	0.020
Shoulders			1.000	0.655	1.000	0.655	0.317
Upper-back				0.564	1.000	0.564	0.157
Middle-back					0.564	1.000	0.317
Lower-back						0.317	0.157
Buttocks							0.317

Vertical random 16 Hz	Head	Neck	Upper-back	Middle-back	Lower-back	Buttocks	Legs	Belly
Head		0.546	0.014	0.054	0.763	0.084	0.024	0.034
Neck			0.084	0.238	0.855	0.234	0.084	0.084
Upper-back				0.655	0.068	0.317	1.000	1.000
Middle-back					0.063	0.705	0.655	0.655
Lower-back						0.129	0.038	0.059
Buttocks							0.157	0.157
Legs								1.000

Static

Friedman

Ranks

	Mean Rank
stneck	3,67
stshou	3,42
stuppba	3,29
stmidba	3,75
stlowba	5,54
stbutt	3,92
stleg	4,42

Test Statistics[a]

N	12,000
Chi-Square	16,290
df	6,000
Asymp. Sig.	,012

a. Friedman Test

Wicoxon: Asymptotic significance

Static	Neck	Shoulders	Upper-back	Middle-back	Lower-back	Buttocks	Legs
Neck		1.0	0.655	0.739	0.026	0.655	0.157
Shoulders			0.564	783	0.015	0.705	0.046
Upper-back				0.414	0.009	0.317	0.096
Middle-back					0.083	1.0	0.380
Lower-back						0.024	0.084
Buttocks							0.366

2. Neck and lower-back discomfort during exposure to vibration versus prolonged static posture

The data are compared at the same duration.

Wilcoxon: Asymptotic significance

Lateral Neck	Static
sinusoidal 1 Hz	0.049
sinusoidal 4 Hz	0.039
random 1 Hz	1
random 4 Hz	0,317
random 8 Hz	0.157
random 16 Hz	0.157
shock	0.317
sinusoidal 1 Hz with harness	0.038

Fore-and-aft Neck	Static
sinusoidal 1 Hz	0.014
sinusoidal 4 Hz	0.008
random 1 Hz	0.023
random 4 Hz	0.180
random 8 Hz	0.317
random 16 Hz	0.157
shock	0,18
sinusoidal 0.5 Hz	0,157

Vertical Neck	Static
sinusoidal 1 Hz	0.564
sinusoidal 4 Hz	0.046
random 1 Hz	0.083
random 4 Hz	0.157
random 8 Hz	0.655
random 16 Hz	0.049
shock	0,564

Lateral Lower back	Static
sinusoidal 1 Hz	0.527
sinusoidal 4 Hz	0.854
random 1 Hz	0.655
random 4 Hz	1.0
random 8 Hz	0.655
random 16 Hz	0.066
shock	0.206
sinusoidal 1 Hz with harness	1.0

Fore-and-aft Lower back	Static
sinusoidal 1 Hz	0.705
sinusoidal 4 Hz	0.102
random 1 Hz	0.06
random 4 Hz	0.064
random 8 Hz	0.564
random 16 Hz	0.083
shock	0.014
sinusoidal 0.5 Hz	0.655

Vertical Lower back	Static
sinusoidal 1 Hz	0.024
sinusoidal 4 Hz	0.020
random 1 Hz	0.163
random 4 Hz	0,068
random 8 Hz	0.564
random 16 Hz	0.564
shock	0,068

3. Effects of the direction of excitation on the neck discomfort during prolonged exposure to vibration

Friedman

Ranks

	Mean Rank
ls4neck	2,19
fs4neck	2,00
vs4neck	1,81

Test Statistics[a]

N	8,000
Chi-Square	1,000
df	2,000
Asymp. Sig.	,607

a. Friedman Test

Ranks

	Mean Rank
ls1neck	2,50
fs1neck	2,00
vs1neck	1,50

Test Statistics[a]

N	8,000
Chi-Square	6,737
df	2,000
Asymp. Sig.	,034

a. Friedman Test

Ranks

	Mean Rank
lr4neck	1,75
fr4neck	2,31
vr4neck	1,94

Test Statistics[a]

N	8,000
Chi-Square	2,800
df	2,000
Asymp. Sig.	,247

a. Friedman Test

Ranks

	Mean Rank
lr1neck	1,75
fr1neck	2,38
vr1neck	1,88

Test Statistics[a]

N	8,000
Chi-Square	6,500
df	2,000
Asymp. Sig.	,050

a. Friedman Test

Ranks

	Mean Rank
lshneck	2,17
fshneck	2,00
vshneck	1,83

Test Statistics[a]

N	9,000
Chi-Square	1,200
df	2,000
Asymp. Sig.	,549

a. Friedman Test

Ranks

	Mean Rank
lr8neck	2,00
fr8neck	1,83
vr8neck	2,17

Test Statistics[a]

N	9,000
Chi-Square	1,200
df	2,000
Asymp. Sig.	,549

a. Friedman Test

Ranks

	Mean Rank
lr16neck	1,94
fr16neck	1,61
vr16neck	2,44

Test Statistics[a]

N	9,000
Chi-Square	6,333
df	2,000
Asymp. Sig.	,042

a. Friedman Test

Wilcoxon

Neck	Lateral vs Fore-and-aft	Lateral vs Vertical	Fore-and-aft vs Vertical
Sinusoid 1 Hz	0.047	0.034	0.046
Random 1 Hz	0.050	0.564	0.129
Random 16 Hz	0.257	0.157	0.034

4. Effects of the waveform of excitation on the neck discomfort during prolonged exposure to vibration

Wilcoxon: Asymptotic significance

Neck	1 Hz			4 Hz
	Sinusoid vs Random	Random vs Shock	Sinusoid vs Shock	Sinusoid vs Random
Lateral	0.161	0.317	0.038	0.026
Fore-and-aft	0.763	0.305	0.187	0.157
Vertical	0.564	1.0	0.705	0.059

5. Effects of the frequency of excitation on the neck discomfort during prolonged exposure to vibration

Friedman

Ranks

	Mean Rank
lr8neck	2,92
lr16neck	2,58
lr1neck30	2,25
lr4neck30	2,25

Test Statistics[a]

N	6,000
Chi-Square	2,538
df	3,000
Asymp. Sig.	,468

a. Friedman Test

Ranks

	Mean Rank
vr8neck	2,21
vr16neck	3,07
vr1neck30	2,71
vr4neck30	2,00

Test Statistics[a]

N	7,000
Chi-Square	4,140
df	3,000
Asymp. Sig.	,247

a. Friedman Test

Ranks

	Mean Rank
fr8neck	2,17
fr16neck	2,50
fr1neck30	2,83
fr4neck30	2,50

Test Statistics[a]

N	6,000
Chi-Square	1,714
df	3,000
Asymp. Sig.	,634

a. Friedman Test

Ranks

	Mean Rank
fs05neck	2,00
fs1neck20	1,75
fs4neck20	2,25

Test Statistics[a]

N	6,000
Chi-Square	3,000
df	2,000
Asymp. Sig.	,223

a. Friedman Test

Wilcoxon: Asymptotic significance

Neck	Sinusoid
	1 Hz vs 4 Hz
Lateral	0.301
Fore-and-aft	0.317
Vertical	0.059

6. Effects of the frequency of excitation on the neck discomfort during prolonged exposure to vibration

Neck	Sinusoid 1 Hz lateral with harness
Sinusoid 1 Hz lateral	0.046

APPENDIX 3 :

Subjects' Instructions

Subjective studies

The experimenters would like to thank you for participating to this experiment.

During this experiment you will be seated on a conventional car seat. You need to wear the seat belt. You will also need to wear headphone and blindfold. In case of emergency you can push the stop button.

You may leave the experiment at any time, please inform the experimenter if it is the case.

You will be exposed to whole-body vibration during one hour. You will need to perform two tasks:

- During the first ten seconds of exposure to vibration, you will focus on the discomfort experienced. You will be asked to keep constant this discomfort by adjusting the level of the vibration magnitude with a knob. For example if you feel that your discomfort is increasing, you should turn the knob so as to reduce the level of the vibration magnitude and your discomfort.
- Every ten minutes, you will also be asked to determine the body location of most discomfort and rate this discomfort with the 5 points semantic scale given below. You will then be asked to define any other locations of discomfort with their corresponding discomfort rating.

5 points semantic scale (from BD 6841 1987):

0	Not uncomfortable
1	Little uncomfortable
2	Fairly uncomfortable
3	Uncomfortable
4	Very uncomfortable
5	Extremely uncomfortable