Number of pages: 32

Number of tables: 4

Number of Figures: 8

Number of references: 25

A Variable Parameter Single Degree-of-Freedom Model for Predicting the Effects of Sitting Posture and Vibration Magnitude on the Vertical Apparent Mass of the Human Body

Running title: POSTURE AND MAGNITUDE DEPENDANT APPARENT MASS MODEL

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Abstract

Models of the vertical apparent mass of the human body are mostly restricted to a sitting posture unsupported by a backrest and ignore the variations in apparent mass associated with changes in posture and changes in the magnitude of vibration. Using findings from experimental research, this study fitted a single degree-of-freedom lumped parameter model to the measured vertical apparent mass of the body measured with a range of sitting postures and vibration magnitudes. The resulting model reflects the effects of reclining a rigid backrest or reclining a foam backrest (from 0 to 30 degrees), the effects of moving the hands from the lap to a steering wheel, the effects of moving the horizontal position of the feet, and the effects of vibration magnitude (from 0.125 to 1.6 ms^{-2} r.m.s.). The error between the modelled and the measured apparent mass was minimised, for both the apparent masses of individual subjects and the median apparent masses of groups of 12 subjects, for each sitting posture and each vibration magnitude. Trends in model parameters, the damping ratios, and the damped natural frequencies were identified as a function of the model variables and show the effects of posture and vibration magnitude on body dynamics. For example, contact with a rigid backrest increased the derived damped natural frequency of the principal resonance as a result of reduced moving mass and increased stiffness. When the rigid backrest was reclined from 0 to 30°, the damping decreased and the resonance frequency increased as a result of reduced moving mass. It is concluded that, by appropriate variations in model parameters, a single degree-of-freedom model can provide a useful fit to the vertical apparent mass of the human body over a wide range of postures and vibration magnitudes. When measuring or modelling seat transmissibility, it may be difficult to justify an apparent mass model with more than a single degree-of-freedom if it does not reflect the large influences of vibration magnitude, body posture, and individual variability.

Keywords: apparent mass; biodynamics; seats; whole-body vibration; backrests; posture; magnitude; modelling.

1. Introduction

The transmission of vibration through a seat depends on the dynamic characteristics of the seat and the dynamic characteristics of the body supported on the seat. Mostly, seat transmissibilities are measured with 'representative' people sitting in the seats, but this means different transmissibilities are obtained according to the people selected. Furthermore, this involves exposing the selected people to vibration, with attendant costs and risks. A convenient alternative would be to either replace the person with a dynamic dummy having dynamic characteristics similar to the 'average person', or to calculate the transmissibility from the measured dynamic characteristics of the seat and the known dynamic characteristics of appropriate people. Both approaches need information on the relevant dynamic characteristics of the human body (e.g. a dynamic 'model' of the body).

Models of the dynamic responses of the human body may: (i) represent understanding of how the body moves (i.e. 'mechanistic models'), (ii) summarise biodynamic measurements (i.e. 'quantitative models'), or (iii) provide predictions of the effects of vibration on human health, comfort, or performance (i.e. 'effects models')[1)]. It is now easy to develop and run complex finite element models (e.g.,[2)]) and multi-body models (e.g.,[3)]) of the body that are limited not by the complexity of the model but by the availability of reliable information on the in-vivo characteristics of body tissues and the measured gross dynamic behaviour of the body. Limitations to the availability of information on the dynamic responses of the body is such that it is very common for models to be developed with a complexity far greater than can be justified by the information on which they are based. While some such complex models may develop to provide useful insights into the dynamic behaviour of the body, their complexity is not yet appropriate for representing the responses needed to predict seat transmissibility (e.g. the apparent mass of the body). Indeed, current models mostly fail to reflect factors that are known to alter the dynamic response of the body and that can be expected also to alter seat transmissibility (e.g. the dynamic non-linearity of the body and the effects of body posture).

Simple lumped parameter models have been found to provide very close representations of the apparent mass of the human body sitting on a rigid seat with no backrest contact[4)]. Although models with several degrees of freedom are needed to represent the modulus and phase of both the in-line apparent mass and the cross-axis apparent mass, or the motions of the spine (e.g.[5,6)]), a simple two-degree of freedom model can provide a very accurate representation of the in-line vertical apparent mass[4)], and a simple single degree-of-freedom model may be sufficient for very many purposes[4,7)].

Laboratory experimental studies have shown large changes in the vertical apparent mass of the body as a result of changes in sitting posture. Compared with sitting without a backrest, it has been reported that the principal resonance frequency of the body increases when supported by a reclined rigid backrest[8-10)] and that holding a steering wheel reduces the apparent mass at resonance[8-9)]. Reclining a rigid backrest from 0 to 30 degrees increased the median resonance frequency from 5.5 to 6.4 Hz, whereas the same inclination of a foam backrest decreased the resonance frequency from 5.2 Hz to 4.5 Hz[11)]. When the hands hold a steering wheel, the magnitude of the primary resonance decreases as the steering wheel is moved further away from the body, and a further resonance at around 4 Hz emerges; moving the feet forward from the seated body increases the apparent mass at resonance[12)].

The dynamic responses of the human body are non-linear with respect to vibration magnitude[7]. For example, with subjects sitting upright with no backrest, the resonance frequency in the apparent mass decreased from 5.25 to 4.25 Hz when the magnitude of random vibration increased from 0.35 to 1.4 ms^{-2} r.m.s.[13)]. Similar non-linearities in biodynamic responses have been observed with subjects supported by an upright rigid backrest[14) and with a reclined rigid backrest[8). Non-linearity is reduced when muscle tension is increased in the buttocks or abdomen, suggesting that passive or active changes in the muscles are involved in non-linearity[13).

Although experimental data have shown clear effects of posture and vibration magnitude on the apparent mass of the body, a model reflecting the influence of these factors has not previously been developed. This study was designed to determine the simplest possible lumped parameter model of the vertical apparent mass of the human body that could take into account variations in backrest contact, backrest inclination, hand position, footrest position, and vibration magnitude. It was envisaged that such a model could assist the prediction of the vibration transmitted through seats using either anthropodynamic dummies or mathematical modelling, as well as advancing understanding of the influence of these factors on body dynamics. It was hypothesized that there would be systematic trends in model parameters determined by fitted a simple model to experimental data obtained with variations in backrest contact, backrest inclination, hand position, footrest position, and vibration magnitude.

2 Methods

2.1 Model description and optimisation

The moduli and phases of experimentally determined apparent masses were fitted to the response of a simple single degree-of-freedom lumped parameter model (Figure 1). The model consisted of a base frame with mass m_0 and a suspended structure represented by a single mass, m_1, connected to the base by spring stiffness, k_1, in parallel with damping, c_1.

FIGURE 1 ABOUT HERE

The curve-fitting method used the constrained variable function (fmincon()) within the optimisation toolbox (version 3.1.1) of MATLAB (version 7.4.0.287, R2007a). The target error between the measured and modelled apparent mass response was minimised. The target error was calculated by summing the squares of the errors in the modulus (in kilograms) and the phase (in radians) over the frequency range 1 to 20 Hz. Before summation, an empirically determined weighting of 10 was applied to the phase errors so as to obtain good fits. The base mass in the model was fixed at 6 kg; this was considered the minimum mass that could be mechanically reproduced in an anthropodynamic dummy. The values of the other target parameters were allowed to be any positive value.

Depending on the starting values of the model parameters, fmincon() can identify different local minima. To try to ensure the global minimum was found, the error function was minimized for 24 sets of starting values; the set that led to the minimum error was used. The fitted responses were compared to the measured data to check goodness of fit. Where the apparent mass was modelled as a function of a sequential variable (e.g. increasing backrest angle) the parameter set derived for the previous condition was used as an additional starting set for the next condition.

In order to characterise the response of the model, the damping ratios and damped natural frequencies were also calculated. The damping ratio, ζ , was calculated as: $\xi = \frac{c_1}{2\sqrt{k_1 m_1}}$ with the damped natural frequency, f , derived from the un-damped natural frequency f^n, as $f = f^n\sqrt{1-\varsigma^2}$, with $f^n = \frac{1}{2\pi}\sqrt{\frac{k_1}{m_1}}$.

For each condition, the lumped parameter model was fitted to the median apparent mass of the subject group. To model the effects of continuous variables that influence the apparent mass of the body (e.g. backrest inclination), sets of parameters have been indentified for each measured condition. Trends in parameters were then identified as a function of the condition (e.g. backrest angle).

Non-parametric tests (Wilcoxon matched-pairs signed ranks test for two-related samples and Friedman test for *k* related samples) were employed in the statistical analysis.

2.2 Experimental measurements

The model was fitted to the vertical apparent mass measured at the seat surface in previous experimental studies of factors affecting the dynamic response of the body: investigating the effects of a seat backrest[11)], footrest and steering wheel[12)], and vibration magnitude[15)].

In the experimental studies, the apparent mass was used to describe the biodynamic response and was defined, in the frequency domain, as the complex ratio of force to acceleration at the seat surface. The apparent mass was calculated from the ratio of the cross-spectral density between the force and acceleration at the seat, to the power spectral density of the acceleration at the seat.

Prior to the calculation of the apparent mass, mass cancellation was performed in the time domain to remove the influence of the mass of the top plate from the measured force: the acceleration time-history on the seat surface was multiplied by the mass of the force platform and then subtracted from the measured force.

The experimental arrangement is illustrated in Fig. 2 (the backrest and hand support were not used in all studies). The experimental conditions are summarised below, with further details in the respective papers.

FIGURE 2 ABOUT HERE

In each study, the apparent mass of 12 male subjects was measured. With the exception of the study of the effect of input spectra, the vibration input was broadband random vertical vibration with a nominally flat constant bandwidth spectrum over the frequency range 0.125 to 40 Hz with an overall magnitude of 1.0 ms^{-2} r.m.s.

All experiments were approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiments was given by all subjects.

2.2.1 Backrest contact and backrest angle

The apparent masses of subjects sitting upright with no backrest support were measured. Their apparent mass was also measured when they made contact with a rigid flat backrest, and when they made contact with a 100-mm thick foam backrest supported on the rigid backrest, with the backrest inclined from 0 to 30° in 5° increments. The rigid backrest vibrated vertically in-phase with the vertical vibration at the seat surface.

2.3.3 Steering wheel and footrest

The effect on vertical apparent mass at the seat pan of holding a steering wheel, varying the position of a steering wheel, and varying the fore-and-aft position of a footrest was also measured (Figure 2). At the closest steering wheel position (SH_1), the forearm and upper arm were at 90°. In the furthest position (SH_5), the arms were outstretched. At the closest footrest position (FH_1), the angle between the femur and fibular was 90°. In the furthest position of the footrest (FH_5), the legs were outstretched and the femur and fibular were at 180°.

2.3.5 Input magnitude

The non-linearity of the apparent masses of subjects was quantified with broadband random inputs (0.125 to 25 Hz) presented at six magnitudes of vibration (0.125, 0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.). Subjects sat upright with no backrest support and positioned their feet in a ‘normal’ driving posture.

3 Results

3.1 Backrest

The measured apparent masses of the 12 individuals are compared with the apparent mass of the fitted one degree-of-freedom model in Figure 3 (magnitude) and Figure 4 (phase). Each subplot compares the measured and modelled response for a subject in two conditions: sitting upright with no backrest support and sitting supported by an upright rigid backrest. It can be seen that the simple model was able to provide reasonable fits to all of the measured responses. Between 8 and 15 Hz, another resonance was apparent in the responses of some subjects, with the frequency and magnitude of this resonance varying between subjects: the single degree-of-freedom model was unable to replicate the response of this resonance and so there was some divergence between the measured and fitted modulus in this region. At frequencies greater than about 10 Hz, the modelled phase lag was less than the measured phase lag for most subjects.

FIGURES 3 AND 4 ABOUT HERE

The parameters derived for the model for each subject in both backrest conditions are given in Table 1. When there was contact with the backrest, the fitted median for the moving mass, m_1 decreased from 54.1 kg to 47.7 kg ($p < 0.01$; Wilcoxon), and the stiffness k_1, increased ($p < 0.01$), resulting in an increase in the derived damped natural frequency from 4.9 to 5.9 Hz ($p < 0.01$). There was greater damping ($p < 0.01$) and a greater damping ratio ($p = 0.05$) when there was backrest support.

TABLE 1 ABOUT HERE

The medians of the moduli and phases of the measured apparent masses of the 12 subjects supported by a rigid backrest reclined in 5° increments (from 0 and 30°) are compared to the fitted responses in Figure 5. Again, the single degree-of-freedom model seems to reproduce the median responses up to around 8 Hz and to reflect the trends in the frequency of the primary resonance. The model parameters derived from fitting to the medians of the subject group are shown in Table 2 for inclinations of both the rigid backrest and the foam backrest.

The moving mass, m_1, decreased by 8.7 kg ($p < 0.01$) as the rigid backrest was reclined from 0 to 30°. An increase in the damped natural frequency, from 5.9 to 6.5 Hz as the backrest was reclined to 30° ($p = 0.01$), was primarily due to a progressive decrease in the moving mass as opposed to an increase in the stiffness, k_1 ($p = 0.43$). Since the reduction in damping as the backrest was reclined ($p = 0.01$) would tend to increase the apparent mass at resonance, the reduction in apparent mass with increasing inclination was mainly caused by the decreases in the moving mass, m_1.

Between 0 and 15° the moving mass was not affected by backrest inclination ($p > 0.75$, Friedman); reclining the backrest from 15 to 30°, the moving mass decreased ($p < 0.01$) and the damping increased ($p < 0.01$) similar to the rigid backrest. However, unlike the rigid backrest, there was a decrease in the resonance frequency from 5.0 to 4.6 Hz as the foam backrest was reclined from 15 to 30° ($p < 0.01$). Since the moving mass decreased with increasing inclination of the foam backrest, the decrease in resonance frequency was due to a decrease in the stiffness, k_1 ($p < 0.01$).

TABLE 2 ABOUT HERE

The apparent mass between 8 and 15 Hz and the phase at frequencies greater than 8 Hz varied with backrest angle, but this variation was not reflected in the fitted responses.

FIGURE 5 ABOUT HERE

3.2 Posture

When subjects held a steering wheel, a resonance was evident around 4 Hz that was not evident with a 'hands in lap' posture (Figure 6). There was a tendency for this resonance to become more pronounced as the hands moved further away from the body. The single degree-of-freedom model was not able to represent both resonances, resulting in a single peak fitted to both resonances. Consequently, the frequency and magnitude of the derived natural frequency did not only reflect changes in the primary resonance but was also influenced by the resonance around 4 Hz. The effect of this was that the modelled resonance decreased in frequency more, and reduced in magnitude less, compared to the measured primary resonance; this was the case for fits to both the individual and median data. The influence of the resonance at 4 Hz was least when the steering wheel was positioned at its closest position (S_{H1}); the effects on the primary resonance of moving the steering wheel forward from this position were not reflected in the modelled response, consequently only the derived parameters for the 'hands in lap' and the S_{H1} postures are shown (Table 3).

FIGURE 6 AND TABLE 3 ABOUT HERE

When subjects held a steering wheel in position S_{H1}, the median moving mass, m_1, deceased by 3.0 kg compared to the 'hands in lap' posture; indicative of the steering wheel supporting some of the subject weight ($p < 0.01$). The decrease in moving mass and the increase in stiffness ($p < 0.01$) resulted in an increase in the derived damped natural frequency ($p < 0.01$) when subjects held a steering wheel. The damping ($p = 0.56$) and damping ratio ($p = 0.97$) were not affected by moving the hands from the lap to the steering wheel position S_{H1}.

As the feet moved forward, from a position where the lower-legs and the upper-legs were at 90° (F_{H1}) to a position where they were at 45° (F_{H3}), the moving mass increased ($p = 0.02$) but none of the other model parameters were significantly affected (Table 4). Moving the feet forward further from the mid position (F_{H3}), to a position where the legs were outstretched (F_{H5}), there was a further increase in the mass and also a decrease in the resonance frequency ($p < 0.01$) and in the associated stiffness ($p < 0.01$).

3.3 Input magnitude

The effects of the magnitude of vibration on the parameters derived from fitting to the median responses are shown in Table 4. Increasing the magnitude from 0.125 to 1.60 ms^{-2} r.m.s. decreased the natural frequency from 5.8 to 4.6 Hz ($p = 0.01$) in the derived model. As the moving mass was unaffected ($p = 0.86$), this was primarily caused by a decrease in the model stiffness from 86.1 to 54.4 $kN.m^{-1}$ ($p < 0.01$). The fitted damping decreased from 1833 to 1465 Nsm^{-1} ($p < 0.01$) as the magnitude increased from 0.125 to 1.60 ms^{-2} r.m.s.. The damping ratio was not affected ($p = 0.82$).

TABLE 4 ABOUT HERE

4 Discussion

4.1 Relevance to ISO5982:2002[16)]

International Standard 5982:2002[16)] gives idealized values for the apparent mass and the seat-to-head transmissibility of seated people exposed to vertical vibration. The values are intended for the development of mechanical and mathematical models to represent the body and are an amalgamation of several datasets obtained in broadly comparable conditions. The data were acquired with subjects sitting with no backrest and relatively high vibration magnitudes, markedly different from most real world environments.

The single degree-of-freedom model employed in the current study (as shown in Figure 1) has also been fitted to the idealized values of apparent mass given in ISO5982:2002[16)]. It can be seen in Figure 7 that, notwithstanding the simplicity of the model used here, the fitted values are generally within the idealized range in

ISO5982:2002[16] at frequencies less than 20 Hz, although the phase lag at frequencies greater than 15 Hz is slightly less than the upper limit of the phase lag defined in the standard.

FIGURE 7 AROUND HERE

The trends in the model parameters quantified in this study (as shown in Tables 1 to 4) can also be presented as a function of the studied variable (e.g. Figure 8; effect of backrest angle with rigid and foam backrests). Such trends might be used to apply correction factors to idealized values, such as those in ISO5982:2002[16)], so as to adjust for differences between the conditions in which the apparent mass has been measured and an environment in which the data are to be used. For a car driver, for example, the backrest conditions and backrest angle, the footrest position, the hand position, and the vibration magnitude would differ from those assumed in ISO5982:2002. From the data shown here, corrections to the model parameters might be considered for the effects of backrest contact, backrest angle, steering wheel contact, foot position, and the magnitude of vibration.

FIGURE 8 AROUND HERE

4.2 Other applications of the model

Models of the apparent mass of the body that allow for the effects of changes in the posture of subjects or the magnitude of vibration may also be used in the development of anthropodynamic dummies. Variations in model parameters would be difficult to achieve using a dummy constructed with solely passive components (e.g.,[17,18)]) but may be achieved with an active dummy (e.g.,[19,20)]). The response of an active anthropodynamic dummy is partially controlled by an actuator, so the damping and stiffness can be altered without hardware modification. Any interaction of a dummy with the backrest of a seat could influence the dynamic response at the seat pan, so a dummy based solely on the apparent mass at the seat pan should be de-coupled from the seat backrest to produce the required response at the seat surface.

Wei and Griffin[21)] described a method to predict seat transmissibility from measurements of the dynamic stiffness and damping of the seat and a dynamic model of the human body. Their study employed the apparent masses of subjects sitting upright with no backrest while exposed to a single magnitude of vibration. A model with variable parameters as described within this study could be used to make predictions for more realistic seating conditions. This assumes that the apparent mass of the body sitting on a rigid flat seat is sufficiently similar to the apparent mass of the body supported on a compliant seat. The contact area and pressure distribution will differ between rigid and compliant seats and it has been suggested that such differences may affect the apparent mass of the body[22)].

4.3 Model limitations

The response of a two degree-of-freedom model with two single degree-of-freedom structures suspended off a base mass[4)] was also considered in this study. Where the measured apparent mass showed evidence of additional resonances, the resulting fits were noticeably improved but there were fewer statistically significant trends in the model parameters. This reduction in consistency of trends was caused by the variation in the magnitude and frequency of secondary resonances between subjects and between conditions. The difference between the measured and fitted responses with the single degree-of-freedom model was generally much less than the inter-subject variability and also less than the variability between conditions, particularly at frequencies less than 10 Hz, and it was therefore decided that the fits obtained were acceptable for the present purpose.

There were some minor inconsistencies in parameter trends (e.g. Table 2: 20° backrest inclination, higher k_1 value; Table 4: 0.4 ms^{-2} r.m.s., higher m_1 value). Depending on the starting parameters, the fmincon() function can converge on local rather than global minima, but by using a single degree-of-freedom model and multiple starting parameters the likelihood of this is reduced. Inspection of the fits to the data suggest the minor inconsistencies in parameters reflect the underlying data as opposed to problems in converging on global minima.

Inter-subject variability has been shown to have a large effect on apparent mass[7)]. The effect of subject mass on model parameters could be taken into account by fitting the model parameters to the apparent masses of subjects grouped by mass. Increased subject mass tends to increase the apparent mass at all frequencies, and it has been found that inter-subject variability can be reduced by normalising the apparent mass with respect to the subject mass supported on the seat surface[7)]. However, variability still exists in the normalised data, suggesting that physical characteristics of subjects other than their body mass also contribute to variability in apparent mass. Although some of these factors have been investigated (e.g.,[7,23)]) they are not fully understood. The variability between subjects might be investigated by fitting a model to the responses of individual subjects and using regression analysis to identify associations between subject physical characteristics and model parameters.

Other postural and environmental factors have also been found to affect the vertical apparent mass at the seat surface, including seat pan inclination[9,24)], the frequency of vibration[25)], and the thickness of backrest foam[11)]. Although the influence of these factors on apparent mass may sometimes be small relative to the influence of other factors investigated here, systematic investigations are appropriate to better understand the influence of all factors influencing apparent mass and its practical applications.

An increase in the number of degrees-of-freedom in the model employed here would obviously increase the fit between the model and any experimental data. However, a single degree-of-freedom model provides a surprisingly good fit, especially when considering the large variability in apparent mass between people. An additional degree-of-freedom would be beneficial in some postures and with some individuals, but there would appear to be no justification for developing more complex models to predict seat transmissibility if they do not reflect the relatively large effects of vibration magnitude, posture, individual variability and other factors that influence apparent mass and its application to predicting seat transmissibility.

5.0 Conclusions

By appropriate variations in model parameters, a single degree-of-freedom model can provide a useful fit to the measured vertical apparent mass of the human body over a wide range of postures and vibration magnitudes at frequencies less than about 20 Hz. The trends in model parameters that have been determined allow apparent mass to be predicted for combinations of conditions that have not been measured. The findings may assist the development of models for predicting seat transmissibility, including the development of anthropodynamic dummies.

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Table 1 Effect of contact with an upright rigid backrest on parameters generated by fitting a single degree-of-freedom model to the measured vertical apparent masses of 12 subjects (S1-12) and also to the median apparent mass.

	m_0, kg	m_1, kg	k_1, Nm^{-1}	c_1, Nsm^{-1}	f, Hz	ζ, Hz
No backrest						
S1	6.0	74.3	83339	2453	4.6	0.49
S2	6.0	54.9	76276	1528	5.5	0.37
S3	6.0	58.7	88230	1950	5.6	0.43
S4	6.0	45.6	57078	1421	5.1	0.44
S5	6.0	48.7	79181	1499	5.9	0.38
S6	6.0	46.2	56509	1141	5.2	0.35
S7	6.0	51.7	44100	1387	4.1	0.46
S8	6.0	42.7	44286	1356	4.5	0.49
S9	6.0	48.8	30863	1154	3.5	0.47
S10	6.0	45.3	30566	1056	3.7	0.45
S11	6.0	57.5	73159	1256	5.4	0.31
S12	6.0	46.5	72699	1806	5.5	0.49
Median response	*6.0*	*51.4*	*60917*	*1547*	*4.9*	*0.44*
Rigid backrest						
S1	6.0	67.5	106384	2835	5.4	0.53
S2	6.0	51.3	113998	1945	6.9	0.40
S3	6.0	49.5	112315	1830	7.0	0.39
S4	6.0	45.3	77074	1608	5.9	0.43
S5	6.0	48.4	89249	1743	6.2	0.42
S6	6.0	43.7	64558	1229	5.7	0.37
S7	6.0	46.7	65506	1838	5.1	0.53
S8	6.0	40.0	60015	1591	5.3	0.51
S9	6.0	46.4	72418	2171	5.1	0.59
S10	6.0	40.7	62718	1370	5.6	0.43
S11	6.0	51.5	84624	1338	6.1	0.32
S12	6.0	41.8	69086	2045	5.2	0.60
Median response	*6.0*	*47.7*	*82218*	*1798*	*5.9*	*0.45*

Table 2 Effect of backrest type, and backrest angle, on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

	m_0, kg	m_1, kg	k_1, Nm^{-1}	c_1, Nsm^{-1}	f, Hz	ζ, Hz
Rigid backrest angle						
0°	6.0	47.7	81495	1795	5.9	0.46
5°	6.0	47.9	81740	1787	5.9	0.45
10°	6.0	46.2	79996	1757	5.9	0.46
15°	6.0	44.9	79790	1676	6.0	0.44
20°	6.0	43.6	80489	1669	6.1	0.45
25°	6.0	42.5	79373	1609	6.2	0.44
30°	6.0	39.0	78832	1492	6.5	0.43
Foam backrest angle						
0°	6.0	48.3	67745	1623	5.3	0.45
5°	6.0	47.7	66214	1562	5.3	0.44
10°	6.0	47.9	61449	1488	5.1	0.43
15°	6.0	48.4	57519	1415	5.0	0.42
20°	6.0	47.7	54854	1364	4.9	0.42
25°	6.0	47.0	49602	1394	4.6	0.46
30°	6.0	45.1	47978	1350	4.6	0.46

Table 3 Effect of hand and foot position on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

Condition	m_0, kg	m_1, kg	k_1, Nm^{-1}	c_1, Nsm^{-1}	f, Hz	ζ, Hz
Hand position						
Hands in lap (backrest at 15°, feet F_{H4})	6.0	46.6	91324	1598	6.5	0.39
Hands on steering wheel (backrest at 15°, feet F_{H4}, hands S_{H1})	6.0	43.6	101746	1631	7.1	0.39
Footrest position (hands in lap)						
F_{H1} (minimum)	6.0	43.9	95485	1826	6.6	0.45
F_{H2}	6.0	44.6	96946	1848	6.6	0.44
F_{H3} (mid)	6.0	44.6	96946	1848	6.6	0.44
F_{H4}	6.0	46.6	91324	1598	6.5	0.39
F_{H5} (maximum)	6.0	48.8	79278	1661	5.8	0.42

Table 4 Effect of the magnitude of vertical vibration on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects (hands in lap, no backrest contact). [Text in Section 3.3 and Table 4 corrected from what appears in published paper]

Condition	m_0, kg	m_1, kg	k_1, Nm^{-1}	c_1, Nsm^{-1}	f_1, Hz	ζ_1, Hz
Input magnitude, ms^{-2} r.m.s.						
0.13	6.0	52.4	86098	1833	5.8	0.43
0.25	6.0	52.5	79493	1824	5.5	0.45
0.40	6.0	53.5	75372	1743	5.4	0.43
0.60	6.0	52.1	64053	1555	5.0	0.43
1.00	6.0	52.3	60357	1518	4.9	0.43
1.60	6.0	51.7	54379	1465	4.6	0.44

Figure 1 One-degree of freedom model.

Figure 2 Experimental setup used for the measurement of apparent mass (see Toward and Griffin, 2009, 2010).

Figure 3 Effect of backrest contact on the apparent mass moduli of 12 subjects (S1-12) with hands in lap. Comparison of measured (▬▬ no backrest, - - - - upright rigid backrest) and modelled data (—— no backrest, - - - - upright rigid backrest).

Figure 4 Effect of backrest contact on the apparent mass phase of 12 subjects (S1-12) with hands in lap. Comparison of measured (▬▬ no backrest, - - - - upright rigid backrest) and modelled data (—— no backrest, - - - - upright rigid backrest).

Figure 5 Effect of inclination of a rigid backrest on the median vertical apparent masses of 12 subjects measured on the seat. Comparison of modelled and experimental data. ——— , 0°; · · · · · · , 5°; · - · - · - 10°; - - - - - ,15°; ▬▬▬ ,20°; ▪ ▪ ▪ ▪ ▪ ,25°; · ▬ · ▬ · ,30°.

Figure 6 Effect of hand position on the median vertical apparent masses of 12 subjects measured on the seat. Comparison of modelled and experimental data with hands on steering wheel (——— , S_{H5} (max); · · · · · · , S_{H4}; · - · - · - S_{H3}; - - - - - ,S_{H2}; ▬▬▬ ,S_{H1}) and hands in lap (▪ ▪ ▪ ▪ ▪).

Figure 7 Idealized mean (· - · - · -) and limit values (▬▬▬) given in ISO5982:2002[16)] compared to the fitted response of the single degree-of-freedom model (———). Model parameters: m_0 = 6.0 kg, m_1 = 45.5 kg, k_1 = 46361 Nm^{-1}, c_1 = 1470 Nsm^{-1}.

Figure 8 Effect of inclination of rigid backrest (——) and foam backrest (- - -) on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

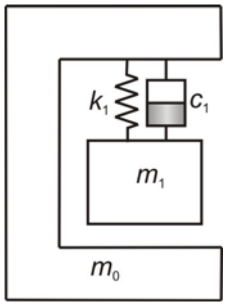

Fig. 1

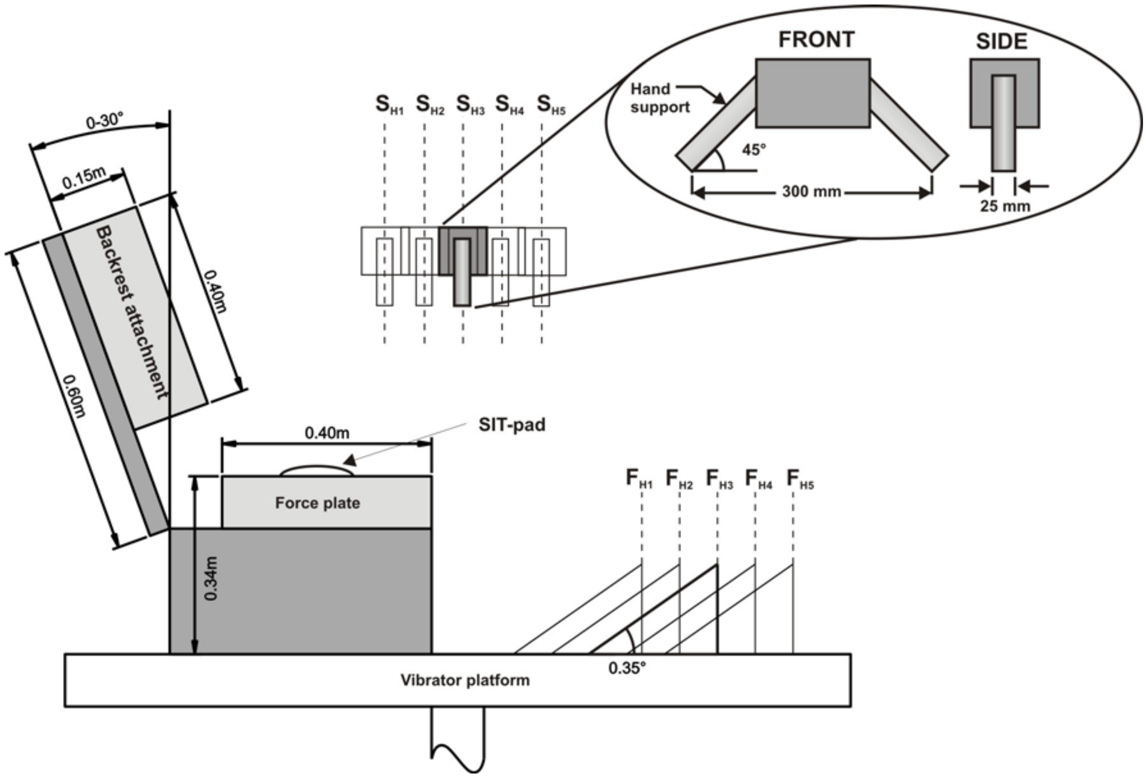
FRONT
SIDE
Hand support
45°
300 mm
25 mm
S H1 S H2 S H3 S H4 S H5
0-30°
0.15m
Backrest attachment
0.40m
0.60m
0.40m
SIT-pad
Force plate
0.34m
F H1 F H2 F H3 F H4 F H5
0.35°
Vibrator platform

Fig. 2

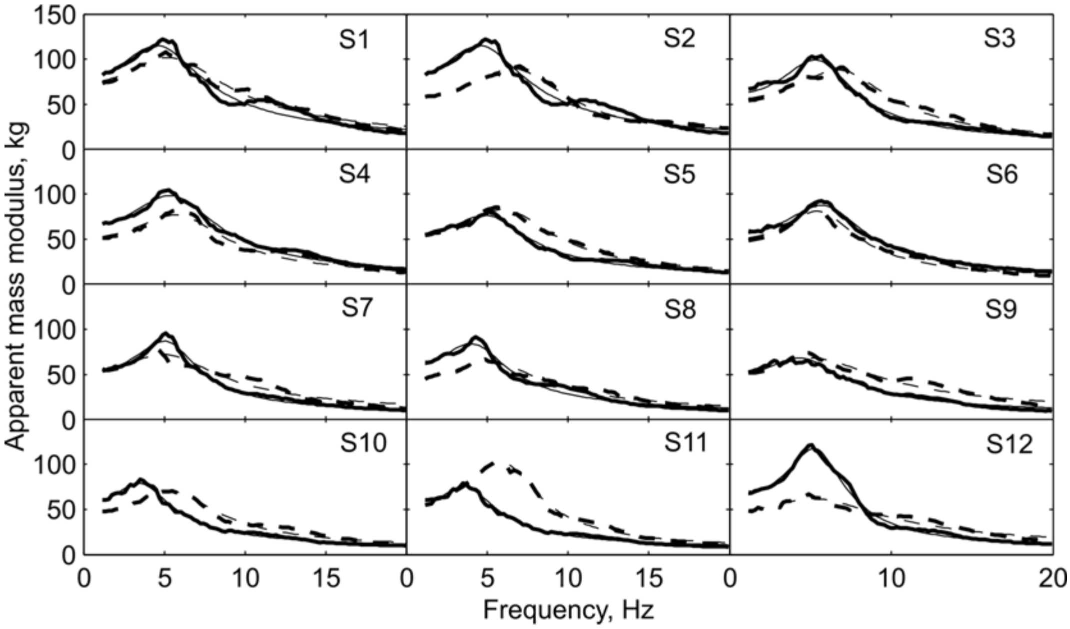
Apparent mass modulus, kg
Frequency, Hz
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
150
100
50
0
0
5
10
15
20

Fig. 3

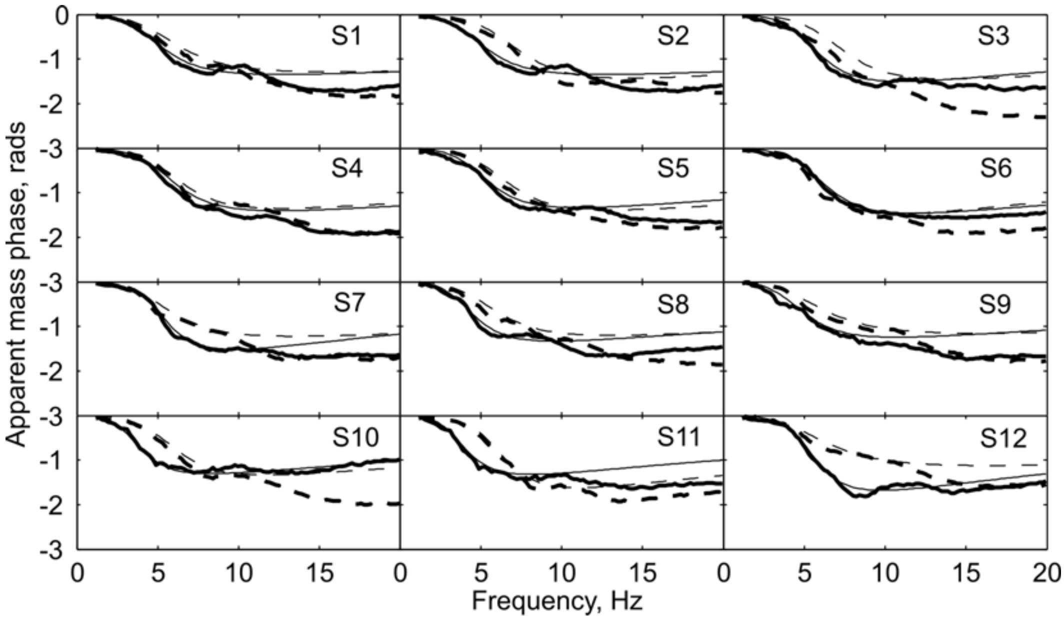
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
Apparent mass phase, rads
0
-1
-2
-3
0
5
10
15
20
Frequency, Hz

Fig. 4

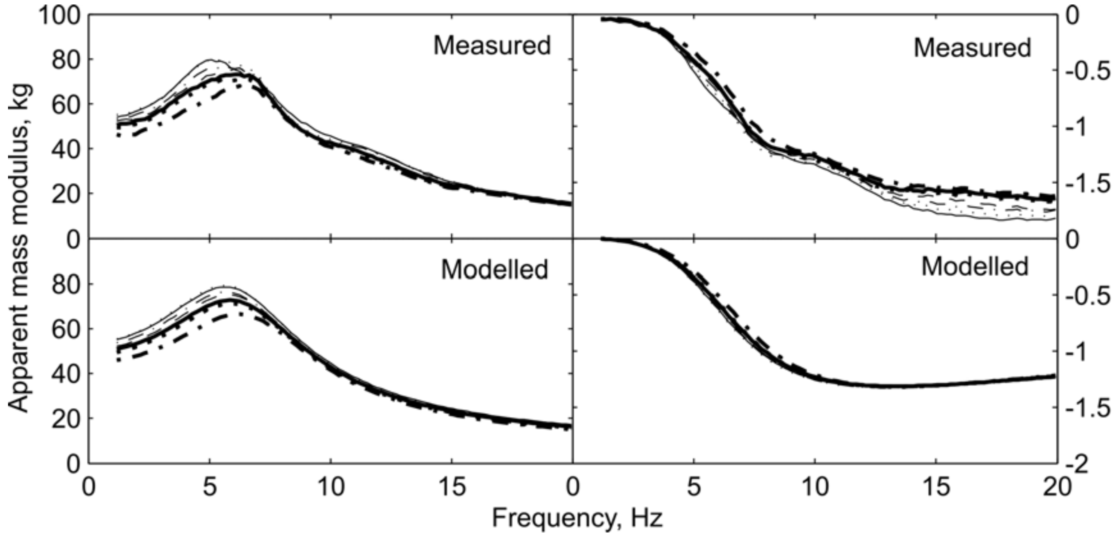
Measured
Measured
Modelled
Modelled
Apparent mass modulus, kg
Apparent mass phase, rads
Frequency, Hz
100
80
60
40
20
0
0
-0.5
-1
-1.5
-2
0
5
10
15
20

Fig. 5

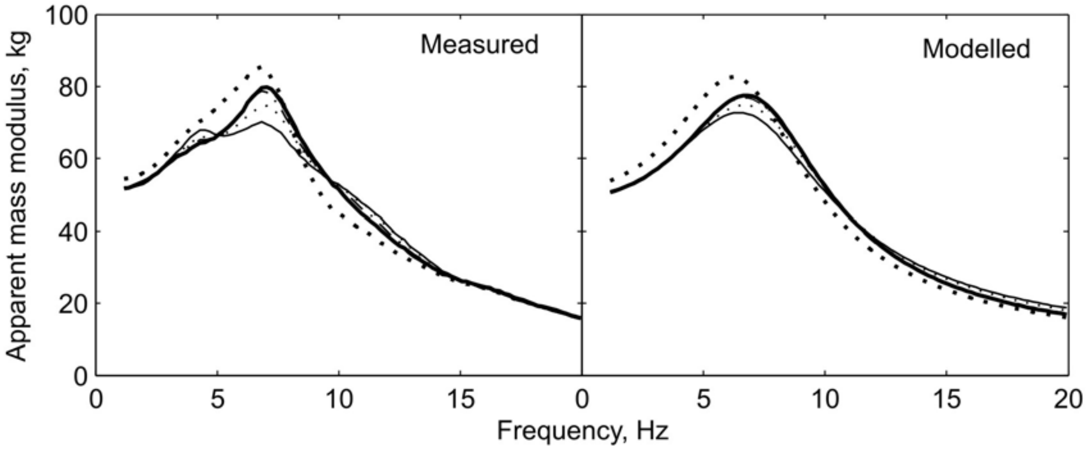
Measured
Modelled
Apparent mass modulus, kg
100
80
60
40
20
0
0
5
10
15
0
5
10
15
20
Frequency, Hz

Fig. 6

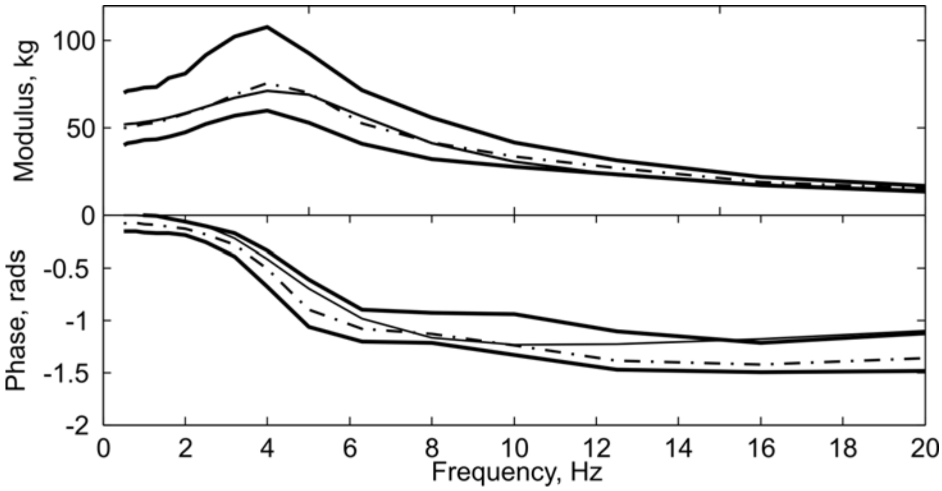
Modulus, kg
100
50
0
Phase, rads
-0.5
-1
-1.5
-2
0
2
4
6
8
10
12
14
16
18
20
Frequency, Hz

Fig. 7

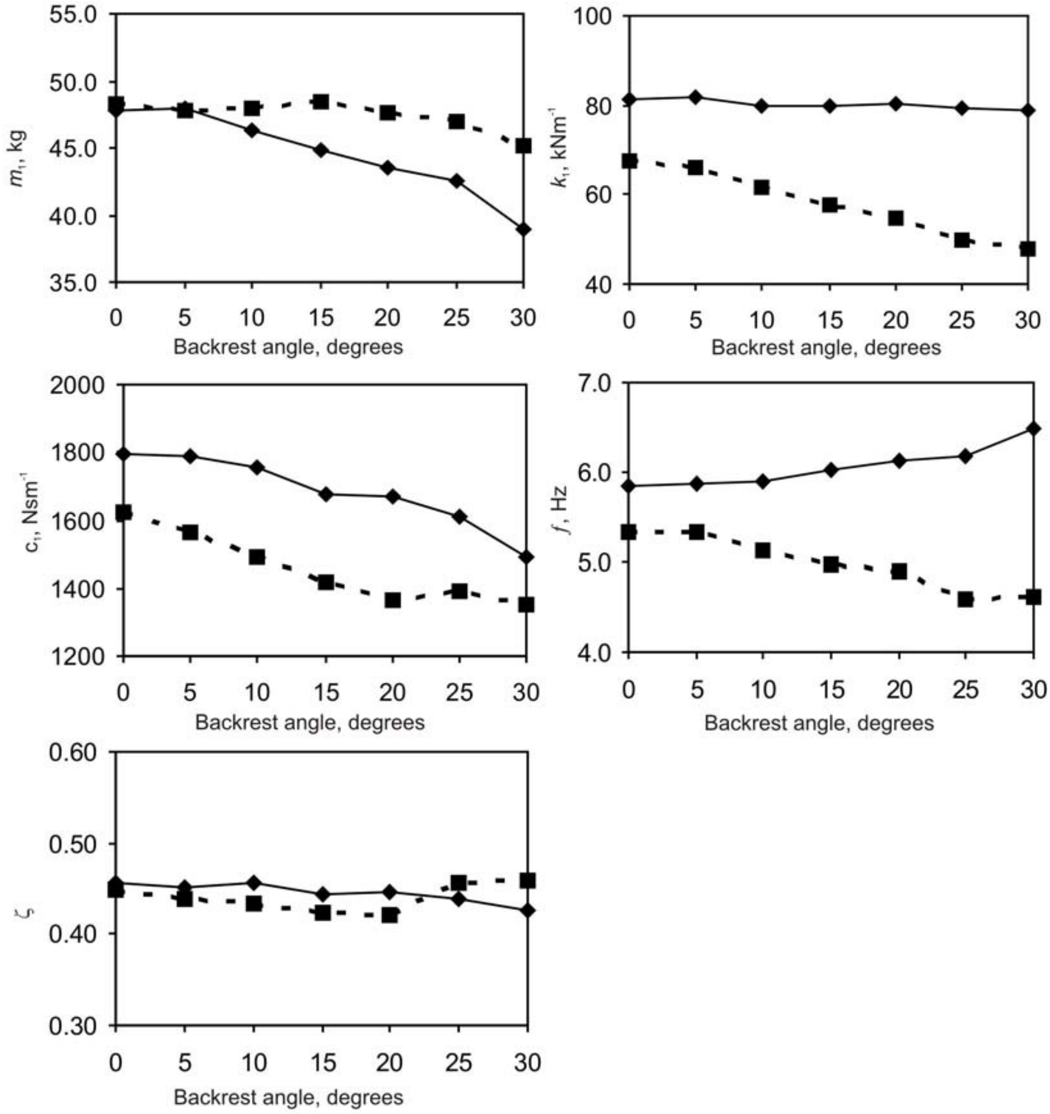
55.0
50.0
45.0
40.0
35.0
m_1, kg
0
5
10
15
20
25
30
Backrest angle, degrees
100
80
60
40
k_1, kNm^{-1}
Backrest angle, degrees
2000
1800
1600
1400
1200
c_1, Nsm^{-1}
Backrest angle, degrees
7.0
6.0
5.0
4.0
f, Hz
Backrest angle, degrees
0.60
0.50
0.40
0.30
ζ
Backrest angle, degrees

Fig. 8