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A BODY MASS DEPENDENT MECHANICAL IMPEDANCE MODEL FOR APPLICATIONS IN VIBRATION SEAT TESTING

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A three degree-of-freedom model is proposed to predict the biodynamic responses of the seated human body of different masses. A baseline model is initially derived to satisfy both the mean apparent mass and seat-to-head transmissibility responses proposed in ISO/DIS 5982:2000 applicable for mean body mass of 75 kg. The validity of the resultant generic mass dependent model is verified by comparing the apparent mass and driving-point mechanical impedance responses computed for total body masses of 55, 75 and 90 kg with the range of idealized values proposed for body masses within the 49–93 kg range. Considering the lack of data that could be found to define the apparent mass/mechanical impedance of subjects with different body masses when applying the experimental conditions defined in ISO/DIS 5982:2000, an attempt is made to adapt the parameters of the base model to fit the measured apparent mass data applicable to groups of automobile occupants within different mass ranges. This is achieved through constrained parametric optimization which consists of minimizing the sum of squared errors between the computed response and the mean apparent mass data measured for automobile occupants within four mass groups: less than 60 kg, 60·5–70·5 kg, 70·5–80 kg and above 80 kg. The results show a reasonably good agreement between the model responses and the measured apparent mass data, particularly at frequencies below 10 Hz. The results suggest that the proposed mass dependent model can effectively predict the apparent mass responses of automobile occupants over a wide range of body masses and for two different postures: passenger (hands-in-lap) and driver (hands-on-steering wheel) postures.

1. INTRODUCTION

The biodynamic response characteristics of seated occupants have been shown to be influenced by several factors, among which body posture, body weight and vibration excitation type and amplitude probably represent the most influential parameters [1, 2]. The wide range of variations observed among the data reported by different investigators for apparent mass, driving-point mechanical impedance and seat-to-head transmissibility is indicative of the influence that these different parameters can have on these response functions. By narrowing down the range of experimental conditions used by different investigators, it has been possible to show that the spread of data can be reduced quite

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significantly [3]. The ranges of idealized values proposed in ISO/DIS 5982 [4] express the values that are most likely to apply for individuals within the mass range 49–93 kg, seated erect without back support, with their feet supported and vibrated, exposed to sinusoidal or broadband random vibration with unweighted root-mean-square acceleration lower than or equal to 5 m/s^2.

In recent years, the applications involving the use of the biodynamic response characteristics of the body have been particularly evidenced in the area of vibration seat testing. It has been well-established that the occupant dynamics contribute considerably to the overall vibration attenuation performance of seats [5]. Current laboratory procedures [6] for assessing vehicle seat performance require the use of volunteer human subjects of specific body masses to act as test loads. For routine testing of seats, the use of human subjects poses several difficulties: lack of repeatability caused by body movement, difficulty in finding subjects having the required body masses, and ethical concerns arising from vibration testing of human subjects. Alternatively, the use of anthropodynamic dummies [7, 8] having representative mechanical impedance characteristics of the human body have been suggested to predict the seat vibration transmissibility characteristics. This approach has been reported to yield good predictions of seat transmissibility when the seat dynamic characteristics, as determined independently using an indenter rig, are combined with the dynamic characteristics of the body [9].

Both the construction of a mechanical dummy and the application of computational procedures rely on the use of biodynamic models applicable over a practical range of variations in the posture, vibration amplitude and body mass. While the reported data may be considered insufficient to establish clear trends with respect to variations in posture and nature of vibration (type and amplitude), sufficient evidence exists to describe the effects of body mass on the biodynamic response. While the effect of body mass on the seat-to-head transmissibility has been explored in only few studies, the effect of body mass on the reported mechanical impedance or apparent mass is more evident. On the basis of limited data on seat-to-head transmissibility, it has been reported that increased body mass could be associated with lower transmissibility magnitude over a wide frequency range [10], while a similar trend could not be identified from the results extracted in another study [11]. Fairley and Griffin [1] reported the vertical apparent mass of 60 seated subjects including men, women and children, which revealed a large scatter of data presumably owing to large variations in the subject masses. The scatter was greatly reduced when the individual curves were normalized with respect to the static seated mass of each subject. In another study performed under narrowband low-frequency vibration containing shocks, Seidel [12] divided the driving-point mechanical impedance data of 37 subjects seated erect without back support into four groups according to the mass range of the subjects involved. These results showed a tendency for the resonant frequency (frequency corresponding to peak modulus of driving-point mechanical impedance) to shift to a lower value and for the peak modulus to increase as the group mean mass increased. At frequencies above resonance, these results further indicated that subject mass had negligible effect on modulus for three of the groups with mean mass lower than 80 kg. The group with mean mass larger than 80 kg showed higher impedance modulus in this frequency range. This trend describing the mass influence at the resonant frequency is also evident from the mechanical impedance of 30 subjects seated erect without backrest reported by Holmlund *et al.* [13] and the apparent mass of 24 subjects seated assuming automotive postures reported by Rakheja *et al.* [14].

The biodynamic models of seated occupants [15, 16] have been invariably derived on the basis of mean response of a population of subjects, where the individual subject masses are known to vary within a certain range. These models may thus be seen to provide a close estimate of the mean response of occupants whose masses correspond to mean mass of groups of subjects employed in the test. The strong dependency of the apparent mass/driving-point mechanical impedance response on the body mass, as evidenced from the data reported in the literature [1], thus cannot generally be characterized using models with fixed mass components. The dependence of the apparent mass/driving-point mechanical impedance response on subject mass is seen to have particular relevance in applications involving vibration transmission of seats or cushions since the energy restoring and dissipative properties of the seat cushions are known to be dependent upon the preload or seated body weight. This is clearly illustrated by the results reported by Wei and Griffin [9], whereby measurements carried out on a car seat and a sample of foam indicate a clear increase in stiffness and damping properties with an increase in preload.

For applications involving evaluations of seat vibration transmissibility, the seat-to-head transmissibility response function is often considered less and consequently the biodynamic models are mostly defined on the basis of either apparent mass or driving-point mechanical impedance functions. Since the model parameters are identified upon fitting a single target response function, the methodology could result in a multitude of model structures and associated parameter combinations that can be found to satisfy the required response, specifically when a multi-d.o.f. model structure is considered. The uniqueness of the model structure and parameters could be considerably enhanced when additional constraints on target functions are introduced. The use of both available functions, the "to the body" (i.e., apparent mass and/or driving-point mechanical impedance) and "through the body" (i.e., seat-to-head transmissibility) transfer functions can help identify a more effective model of the seated occupant. Such methodology may help to enhance the uniqueness of the solution and to ensure that the resulting model response relates more closely to the dynamics of the entire body, while offering the possibility for its use to be extended to applications other than seat testing.

In this study, a generic body mass dependent occupant model is developed, with the objective of providing the basis for constructing mechanical analogues of the human body of different masses for eventual applications in seat/cushion testing. The structure and parameters of the base model are defined to ensure that its response in the 0·5–20 Hz frequency range satisfies the ranges of idealized biodynamic responses defined in ISO/DIS 5982 [4], for the body seated erect without back support, while the feet are supported and vibrated. A semi-definite 3-d.o.f. model structure is chosen to predict the biodynamic responses for body masses ranging from 49 to 93 kg. The applicability of the approach for developing body mass dependent models is then investigated by considering a limiting case where only "to the body" response function is known. This is performed on the basis of apparent mass data reported for 24 subjects within different mass groups, while seated with representative automotive postures for both the passengers and the drivers.

2. BASE MODEL DEVELOPMENT

Based on the analysis of various reported mechanical models [15, 16], a 3-d.o.f. base model with a structure shown in Figure 1 is proposed to represent the portion of the body resting on the seat. This model distinguishes itself from most of the other models in that its structure is chosen such as to satisfy simultaneously both apparent mass/driving-point mechanical impedance and seat-to-head transmissibility data, while minimizing the number of parameters needed to describe the model. The masses m_1 to m_3 are introduced to account for the peak observed in the mean apparent mass response near 4 Hz and the two peaks near 4·5 and 10 Hz in the seat-to-head transmissibility magnitude response shown in ISO/DIS 5982:2000 [2]. These mean response functions are considered to apply to a subject

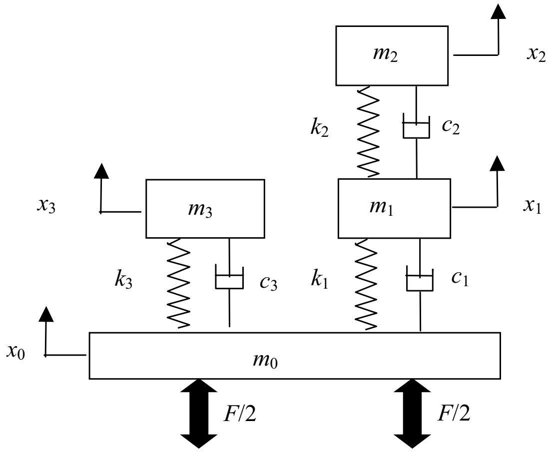

Figure 1. Three-d.o.f. base model structure to represent the seated body portion.

population for which the average subject mass is close to 75 kg. The mass m_0 is introduced to provide flexibility in tuning the model without increasing the number of d.o.f. since its influence is mostly seen on the apparent mass. The masses m_1 and m_2 are introduced to achieve the desired magnitude of vibration transmission through the body. Although the model is not intended to relate to any anatomical structures of the human body, mass m_2 may tentatively be taken to represent the head for the purpose of computing the seat-to-head transmissibility. The sum of the masses, however, is taken to correspond to the body mass supported by the seat.

The equations of motion of the model shown in Figure 1 are formulated as follows:

$$m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_0) + k_1(x_1 - x_0) + c_2(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_2) = 0,$$
$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0$$
$$m_3\ddot{x}_3 + c_3(\dot{x}_3 - \dot{x}_0) + k_3(x_3 - x_0) = 0 \qquad (1)$$

where m_i, c_i and k_i ($i = 1, 2, 3$) are the masses, damping coefficients and stiffness coefficients, respectively, of the model, as shown in Figure 1. x_0 is the displacement of the driving point, and x_1, x_2 and x_3 are displacement co-ordinates of the three model masses.

Laplace transform and solution of equations (1) yield the following expressions for the transfer functions, where each function relates to the ratio of a mass response to the base motion:

$$\frac{X_1(s)}{X_0(s)} = \frac{(c_1 s + k_1)(m_2 s^2 + c_2 s + k_2)}{\Delta(s)},$$
$$\frac{X_2(s)}{X_0(s)} = \frac{(c_1 s + k_1)(c_2 s + k_2)}{\Delta(s)} \quad \text{and} \quad \frac{X_3(s)}{X_0(s)} = \frac{c_3 s + k_3}{m_3 s^2 + c_3 s + k_3}, \qquad (2)$$

where

$$\Delta(s) = [m_1 s^2 + (c_1 + c_2)s + (k_1 + k_2)](m_2 s^2 + c_2 s + k_2) - (c_2 s + k_2)^2. \qquad (3)$$

The apparent mass response of the model is derived from the resultant force at mass m_0 and the driving-point acceleration $\ddot{x}_0$. The resultant force F at the lower mass can be computed from the equation of motion for mass m_0 :

$$m_0\ddot{x}_0 + c_1(\dot{x}_0 - \dot{x}_1) + c_3(\dot{x}_0 - \dot{x}_3) + k_1(x_0 - x_1) + k_3(x_0 - x_3) = F. \tag{4}$$

The solution of equations (1) and (4) yields:

$$F = m_0\ddot{x}_0 + m_1\ddot{x}_1 + m_2\ddot{x}_2 + m_3\ddot{x}_3. \tag{5}$$

The apparent mass response of the model, $M(s)$, can then be derived as follows:

$$M(s) = \frac{F(s)}{s^2X_0(s)} = m_0 + m_1\frac{X_1(s)}{X_0(s)} + m_2\frac{X_2(s)}{X_0(s)} + m_3\frac{X_3(s)}{X_0(s)}. \tag{6}$$

The driving-point mechanical impedance, Z(s), of the model can also be derived from the apparent mass in the following manner:

$$Z(s) = \frac{F(s)}{sX_0(s)} = sM(s). \tag{7}$$

Similarly, the seat-to-head transmissibility response, $T(s)$, of the model is computed from:

$$T(s) = \frac{X_2(s)}{X_0(s)}. \tag{8}$$

2.1. PARAMETER IDENTIFICATION OF THE BASE MODEL

The parameters of the base model shown in Figure 1 are identified through a curve-fitting algorithm in order to achieve a close match of the apparent mass and seat-to-head transmissibility response functions computed from equations (6) and (8), respectively, with corresponding mean values of these functions as proposed in ISO/DIS 5982:2000 [4]. The requirement for matching both these functions is based on the indications that these two biodynamic response functions are somewhat related in providing good correlation in the estimation of the body's primary resonant frequencies [15].

A parametric optimization technique is used to determine the base model parameters whereby an objective function is defined to minimize an error function of computed and mean values of the apparent mass and seat-to-head transmissibility responses proposed in ISO/DIS 5982:2000 [4] in the 0·5–20 Hz frequency range. The objective function is defined by a weighted sum of squared magnitude and phase errors associated with apparent mass and seat-to-head transmissibility functions, respectively, and expressed as

$$U(\chi) = \text{minimize } [\alpha U_M(\chi) + \beta U_T(\chi)], \tag{9}$$

where $U_M(\chi)$ and $U_T(\chi)$ represent the sums of squared errors resulting from apparent mass and seat-to-head transmissibility responses, respectively, given by

$$U_M(\chi) = \sum_{i=1}^{N} \lambda_1\{[|M(\omega_i)| - |M_t(\omega_i)|]\}^2 + \sum_{i=1}^{N} \lambda_2\{[|\phi_M(\omega_i)| - |\phi_{Mt}(\omega_i)|]\}^2,$$

$$U_T(\chi) = \sum_{i=1}^{N} \psi_1\{[|T(\omega_i)| - |T_t(\omega_i)|]\}^2 + \sum_{i=1}^{N} \psi_2\{[|\phi_T(\omega_i)| - |\phi_{Tt}(\omega_i)|]\}^2, \tag{10}$$

where $M(\omega_i)$ and $\phi_M(\omega_i)$ are the apparent mass modulus and phase response of the model, respectively, corresponding to excitation frequency ω_i. $M_t(\omega_i)$ and $\phi_{Mt}(\omega_i)$ are the corresponding mean values proposed in ISO/DIS 5982:2000 [4]. Similarly, $T(\omega_i)$ and $\phi_T(\omega_i)$

represent seat-to-head transmissibility modulus and phase, respectively, as computed from the model, while $T_t(\omega_i)$ and $\phi_{Tt}(\omega_i)$ are the corresponding values as proposed in ISO/DIS 5982:2000 [4]. N is the number of discrete frequencies selected in the 0·5–20 Hz frequency range, and χ is a vector of model parameters to be identified, and expressed as:

$$\chi = \{m_0, m_1, m_2, m_3, c_1, c_2, c_3, k_1, k_2, k_3\}^{\mathrm{T}}, \tag{11}$$

where T designates the transpose, and λ_1 and λ_2 are the weighting factors used in apparent mass modulus and phase error functions, respectively, and ψ_1 and ψ_2 are corresponding weighting factors relating to the seat-to-head transmissibility modulus and phase error functions. These weighting factors are included to ensure somewhat comparable contributions of modulus and phase errors in the objective function. The weighting factors assume different values in different frequency ranges in order to ensure comparable contributions due to low- and high-frequency response characteristics. Since the range of apparent mass modulus and phase are in the same order over the frequency range of interest, the weighting factors λ_1 and λ_2 are taken to be of the same order of magnitude. However, the weighting factors ψ_1 and ψ_2 are taken to differ by an order of magnitude of 10^4 to account for the differences in magnitude between seat-to-head transmissibility modulus (values ranging from 0·65 to 1·5) and phase responses (values ranging from 0 to 120°). The weighting factors α and β, described in equation (9), are chosen to emphasize the contributions due to either apparent mass or seat-to-head transmissibility functions to the total error function. For applications in seating dynamics, the apparent mass response is probably more critical in establishing contributions of the whole-body dynamics to the vibration attenuation performance of seats. A considerably larger value of weighting factor α may thus be selected to emphasize the apparent mass response error in the minimization function.

The minimization problem, expressed in equation (9), is solved subject to constraints applied on the total model mass and on individual model parameters. Since the mean data proposed in ISO/DIS 5982:2000 [4] relate to a mean total body mass of 75 kg, it is estimated that 54·8 kg (i.e., 73% of total body mass [17]) would actually be supported by the seat for subjects adopting an erect seated posture without back support and with the feet resting flat on the base platform. Limit constraints on the total body mass supported by the seat are thus defined to allow the total mass to vary within a narrowband ($\pm$ 4%), such that

$$52{\cdot}8 \leqslant \sum_{0}^{3} m_i \leqslant 57\ \mathrm{kg}. \tag{12}$$

Further constraints imposed on the base model parameters are given by

$$m_i > 0,\ i = 0, 1, 2, 3, \qquad k_i > 0 \quad \text{and} \quad c_i > 0,\ i = 1, 2, 3 \tag{13}$$

The constrained minimization problem, defined in equations (1)–(6) and (8)–(13), was solved using MATLAB software. The solutions were obtained for different starting values of the parameter vector χ, and the resulting model parameters were examined to obtain optimal values and minimum error of the objective function. The different optimization runs corresponding to different starting values converged to similar values of model parameters and error functions. The resulting base model parameters are identified in Table 1.

2.2. BASE MODEL VALIDATION

From the base model parameters appearing in Table 1, it is evident that uncoupled mass m_3 together with its restoring and dissipative elements, k_3 and c_3, primarily describes the

Table 1

Parameters of the base model derived on the basis of mean data proposed in ISO/DIS 5982:2000 [4], $\sum m_i = 55$ kg

Parameter	Value	Parameter	Value	Parameter	Value
m_0 (kg)	2				
m_1 (kg)	6	k_1 (kN/m)	10·0	c_1 (Ns/m)	387
m_2 (kg)	2	k_2 (kN/m)	34·4	c_2 (Ns/m)	234
m_3 (kg)	45	k_3 (kN/m)	36·2	c_3 (Ns/m)	1390

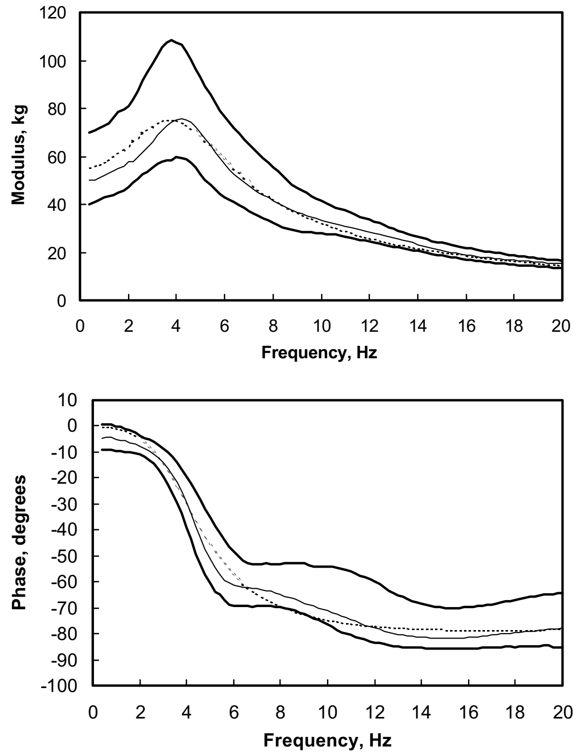

Figure 2. Comparison of the base model predictions of apparent mass - - - - -; with the mean response, ——; and the upper and lower bounds, ━━━━; defining the range of idealized values proposed in ISO/DIS 5982:2000 [4].

apparent mass response in the vicinity of the primary resonant frequency near 4 Hz. The 2-d.o.f. system, comprising m_1 and m_2, primarily determines the seat-to-head transmissibility which shows two modulus peaks near 4·5 and 10 Hz. The validity of the derived model, applicable to a total body mass of 75 kg, is further examined by comparing its apparent mass and seat-to-head transmissibility response functions with the corresponding mean response functions proposed in ISO/DIS 5982 [4]. The apparent mass and seat-to-head transmissibility modulus and phase response characteristics of the base model are presented in Figures 2 and 3 respectively. The figures also present a comparison of the model response functions with the mean and range of idealized values proposed in ISO/DIS 5982:2000 [4].

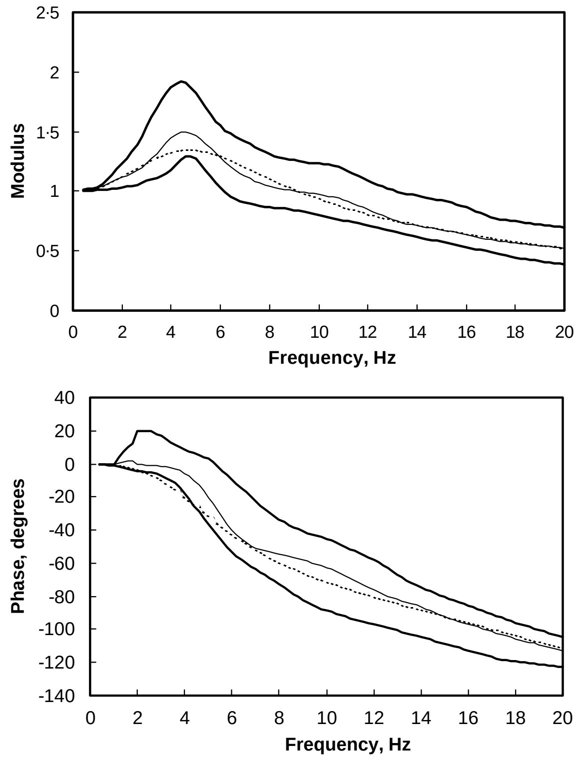

Figure 3. Comparison of the base model predictions of seat-to-head transmissibility -----; with the mean response, ——; and the upper and lower bounds, ———; defining the range of idealized values proposed in ISO/DIS 5982:2000 [4].

The results in terms of modulus and phase show reasonably good agreement between the model response and the mean curves proposed in ISO/DIS 5982:2000 [4] for both apparent mass and seat-to-head transmissibility. The apparent mass modulus response of the base model deviates slightly from the mean ISO/DIS 5982:2000 proposed curve at frequencies below 4 Hz and within the range 10–14 Hz, and the frequency at which peak response occurs is slightly lower than that of the target response curve. However, the computed base model response in terms of apparent mass modulus and phase is found to fall well within the range of idealized values as defined in ISO/DIS 5982:2000 [4] over the entire frequency range from 0·5 to 20 Hz. As for seat-to-head transmissibility, the peak modulus response as computed from the base model is found to be lower than that defined by the target values proposed in ISO/DIS 5982:2000 [4], and the peak response is found to occur at a higher frequency than that defined by the target response curve. At frequencies above and below the resonant frequency peak, the computed response is seen to correlate reasonably well with the target values and generally lies within the bounds defined in ISO/DIS 5982:2000, except perhaps in the 2–4 Hz range where the phase response gets slightly below the lower bound. The complexities associated with simultaneously matching both the apparent mass and seat-to-head transmissibility response functions prevent the base model from providing a better agreement with the desired data at all frequencies within the range of interest.

An eigenvalue analysis performed on the base model with the derived parameters has shown that the model has three modes for which the undamped natural frequencies and damping ratios are 4·5 Hz and 0·545, respectively, for the first mode, 5·7 Hz and 0·675,

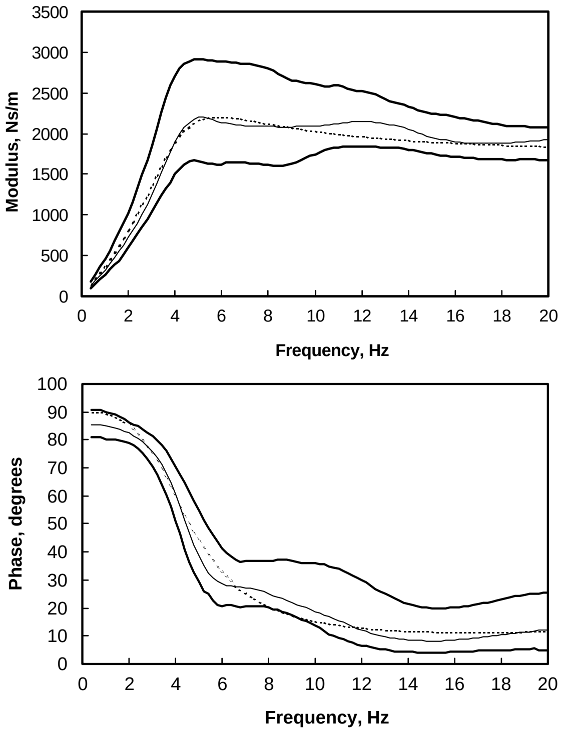

Figure 4. Comparison of the base model predictions of driving-point mechanical impedance, -----; with the mean response, ——; and the upper and lower bounds, ━━━; defining the range of idealized values proposed in ISO/DIS 5982:2000 [4].

respectively, for the second mode and 20·8 Hz and 0·446, respectively, for the third mode. The first mode frequency of 4·5 Hz corresponds well with the natural frequency of mass m_3 for which the damped natural frequency is indicated by a response peak shown to be close to 3·8 Hz in the modulus of apparent mass. The second natural frequency of the model can be related to the damped response of masses m_1 and m_2 whose contributions are represented by a peak response occurring at a frequency close to 4·4 Hz in the seat-to-head transmissibility modulus. As for the third mode, its occurrence is not detected in either of the two response curves in view of the proximity of this frequency with the upper limit of the range of interest.

Since it is also customary to present the biodynamic response in terms of driving-point mechanical impedance, the base model response is derived in terms of the modulus and phase of this function, using equation (7), and compared with the mean and range of idealized values proposed in ISO/DIS 5982:2000 [4], as shown in Figure 4. The computed base model response shows generally good agreement with the ISO/DIS 5982:2000 [4] proposed mean curve, but is unable to reproduce the second peak which is represented in the modulus of the driving-point mechanical impedance target curve near 12 Hz. The resulting base model response, however, is found to fall within the proposed range of idealized values over the entire frequency range for both the modulus and the phase.

3. DEVELOPMENT OF A GENERIC BODY MASS DEPENDENT MODEL

On the basis of the base model, it is proposed to derive a generic body mass dependent model to represent the driving-point mechanical impedance and apparent mass characteristics applicable to seated subjects whose masses can be associated with the test loads required as part of laboratory procedures defined for estimating the vibration attenuation performance of vehicle seats. In general, these procedures require that the tests be conducted with subjects whose masses are representative of the upper and lower bounds of the weight distribution of the population for which the seats are intended. For the evaluation of seats intended for use in earth-moving machinery for example, the ISO 7096:2000 standard [18] recommends the use of two subjects with masses of 55 kg (i.e., 52–55 kg) and 98 kg (i.e., 98–103 kg) when performing the tests with the simulated input characterizing the vehicle vibration. It is thus desirable to derive a body mass dependent generic model that can account for the mechanical impedance/apparent mass characteristics that would likely apply to populations of subjects whose mean masses are close to those that are likely to be recommended as part of procedures for testing seats under laboratory conditions.

3.1. IDENTIFICATION OF GENERIC MASS DEPENDENT MODEL PARAMETERS

The base model represented in Figure 1 is considered as the basis for developing a generic mass dependent model representing the mechanical impedance/apparent mass characteristics of subjects with total mean body masses fixed at 55, 75 and 90 kg. In this formulation, similar posture and vibration characteristics are assumed such that the corresponding ranges of idealized values as defined for these functions in ISO/DIS 5982:2000 [4] are judged to be applicable. The standard proposes ranges of idealized values of driving-point mechanical impedance and apparent mass applicable for subjects with mass in the 49–93 kg range, and seated erect posture without backrest support, while the feet are supported and vibrated. The standard also suggests that the proposed ranges are applicable under sine and random excitations with unweighted r.m.s. acceleration ranging from 0·5 to 3 m/s^2. The mean curves proposed in ISO/DIS 5982:2000 [4] are associated with a mean body mass of 75 kg, as determined from the mean masses of subjects involved in various reported data sets that were used for defining the idealized ranges. Although the upper and lower bounds of the proposed response functions do not relate to any specific body mass, they can be considered to describe the limits within which would be expected to lie the mean responses of any groups of subjects whose mean body masses are within the 49–93 kg range, provided that all the conditions defined in the standard are respected.

The driving-point mechanical impedance/apparent mass dependence on body mass is incorporated within the base model, shown in Figure 1, by modifying the base model parameters reported in Table 1 to ensure the definition of an appropriate generic mass dependent model for total body masses fixed at 55, 75 and 90 kg. It should be noted that the base model parameters were derived in order to match both the mean apparent mass/mechanical impedance and seat-to-head transmissibility characteristics defined in ISO/DIS 5982:2000 [4]. In view of the lack of a clear evidence of the influence of body mass on seat-to-head transmissibility, the variations in the base model parameters are taken to be constrained to provide minimal effect on this response function. Moreover, from a practical point of view, it may be preferable to vary a limited number of parameters to facilitate the application of a generic model for realization of an anthropodynamic dummy for seat testing. An examination of the model response as a function of its masses suggests that its seat-to-head transmissibility response is mostly determined by m_1 and m_2. A slight variation in these masses, would be likely to cause the seat-to-head transmissibility to deviate from the range of idealized values, while the stiffness and damping parameters are maintained equal to their base values. A generic body mass dependent model could thus be

TABLE 2

Parameters of the generic mass dependent model

Parameter	Parameter values		
	55 kg	75 kg	90 kg
m_0 (kg)	2	2	2
m_1 (kg)	6	6	6
m_2 (kg)	2	2	2
m_3 (kg)	30	45	56
$\sum m_i$	40	55	66

conveniently derived by fixing these masses to their base values. As there is no basis for deciding how the stiffness and damping characteristics would actually depend on subject mass, these parameters are considered to remain fixed, thus leaving only two masses m_0 and m_3 to account for mass dependency. An examination of the base model parameters and equation (6) further suggests that the apparent mass response function is mostly affected by mass m_3 alone, while mass m_0 is considerably small. The variations in mass m_3 alone are thus considered to realize a body mass dependent seated occupant model. This single mass variation is seen to enhance the practicality of the mass-dependent model for constructing mechanical analogues and to prevent any variation of the seat-to-head transmissibility response likely to be caused if other masses were allowed to change.

By allowing mass m_3 to take on values of 30, 45 and 56 kg, corresponding values of mean total body masses are taken to be 55, 75 and 90 kg, respectively, where it is assumed that 73% of the total body mass would actually rest on the seat for subjects maintaining an erect seated posture without backrest support, and with feet supported and vibrated [17]. For the generic mass dependent model, all the model parameters are thus considered to remain equal to their base values listed in Table 1, except for m_3 which is taken to assume the values listed above for different total body masses. Table 2 provides a summary of the resulting mass model parameters applicable to the generic mass dependent model.

3.2. GENERIC MASS-DEPENDENT MODEL RESPONSES

Equations (6) and (7) are solved in conjunction with model parameters listed in Table 2 to derive the apparent mass and driving-point mechanical impedance responses of the generic mass dependent model. The results are illustrated in Figures 5 and 6 for apparent mass and driving-point mechanical impedance, respectively, where the curves defining the upper and lower bounds of the ranges of idealized values proposed in ISO/DIS 5982:2000 [4] are also shown.

The results generally suggest that the modulus of the apparent mass and driving-point mechanical impedance increases with body mass at frequencies below 12 Hz, with a clear tendency for the peak modulus to shift to a lower frequency as the mass increases. This tendency agrees with the trends reported in investigations by Seidel [12], Holmlund *et al.* [13] and Rakheja *et al.* [14] in which the influence of subject mass on apparent mass and driving-point mechanical impedance was clearly investigated. At frequencies above 12 Hz, however, the results show negligible mass influence on the modulus of these response functions. While Seidel's data [12] have suggested that this may perhaps be the case

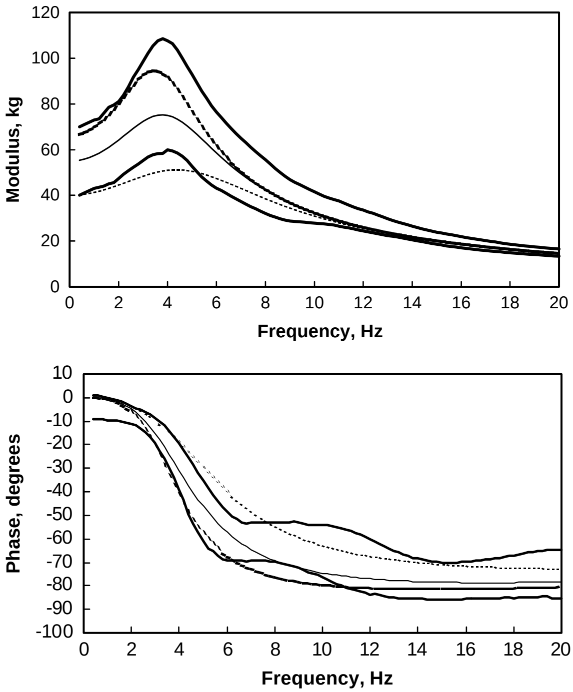

Figure 5. Apparent mass predictions of the generic mass-dependent model for total body masses of 55 kg, - - - - -; 75 kg, ——; and 90 kg, - - - - -; and comparison with the upper and lower bounds, ——; defining the range of idealized values proposed in ISO/DIS 5982:2000 [4].

whenever the subject group masses are maintained below 80 kg, the same study has also concluded that subjects with masses larger than 80 kg could exhibit a modulus of mechanical impedance that is distinctly higher than that of the lower mass groups at higher frequencies. For subjects maintaining postures applicable for automobile occupants, the data reported by Rakheja *et al.* [14] have suggested an increase in the modulus of apparent mass with subject mass over the entire frequency range investigated (0·5 to 40 Hz), although the mass influence was relatively small at frequencies above 10 Hz. Whether these apparent discrepancies in reported trends at higher frequencies are linked to the differences in the experimental conditions (posture, back, feet and hand support conditions, vibration characteristics and excitation levels) used in various investigations is not known at this stage. For applications involving assessment of vibration attenuation performance of vehicle seats, however, it may be sufficient to consider that both the predicted responses of the generic mass dependent model and currently available data show similar trends within the frequency range in which the evaluation of most vehicle seats and cushions is likely to be performed (<12 Hz).

Since there are no data available to compare specifically with the model predictions shown in Figures 5 and 6 for groups of subjects with mean masses of 55, 75 and 90 kg, a direct validation of the proposed generic mass dependent model cannot be made. The model predictions shown in Figures 5 and 6, however, indicate that the response functions defined for group masses of 55, 75 and 90 kg fall reasonably well within the ranges of idealized values proposed in ISO/DIS 5982:2000 [4] which are considered to be applicable to subjects with mean group masses ranging from 49 to 93 kg. The largest discrepancies with respect to the modulus of the apparent mass and driving-point mechanical impedance

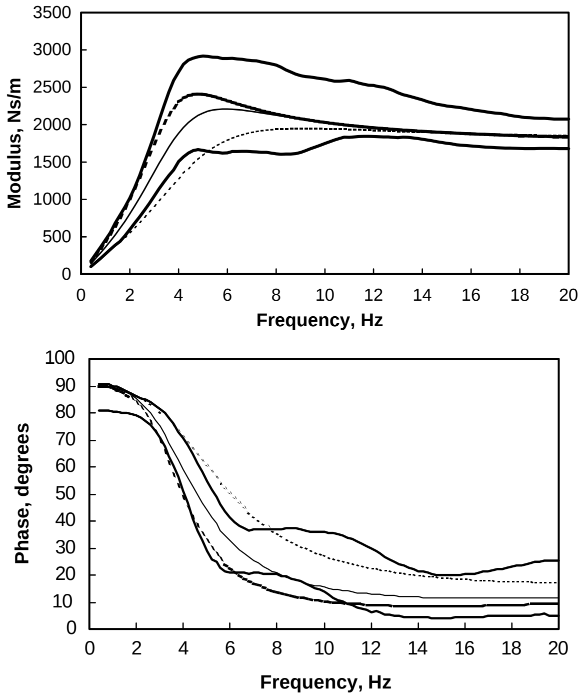

Figure 6. Driving-point mechanical impedance predictions of the generic mass-dependent model for total body masses of 55 kg, - - - - -; 75 kg, ——; and 90 kg, - - - - -; and comparison with the upper and lower bounds, ———; defining the range of idealized values proposed in ISO/DIS 5982:2000 [4].

functions are seen to occur for the group mass of 55 kg, for which the model predictions fall slightly below the lower bound at frequencies below 5 Hz. This could be expected considering the uncertainty associated with the lower bound of the range of idealized values defined in ISO/DIS 5982:2000 [4] which was derived for a mean subject mass of 49 kg with very few data available for subjects within the lower mass range. The phase response, on the other hand, is seen to fall slightly outside the bounds for both group masses of 55 and 90 kg, within very limited frequency ranges.

4. APPLICATION OF THE GENERIC BODY MASS DEPENDENT MODEL FOR SEATED AUTOMOBILE OCCUPANTS

In view of the lack of sufficient data describing the body mass dependence of "to-the-body response", the validity of the proposed methodology and the generic model are examined with respect to the available apparent mass data for 24 seated subjects assuming automotive postures. This however constitutes a limiting case of the proposed methodology, since the corresponding seat-to-head transmissibility data were not available. The model development thus needs to rely entirely upon data reported for a single "to the body" response function. For the example, the data considered correspond to the apparent mass response reported by Rakheja *et al.* [14] for automobile occupants maintaining a seated posture with both hands-in-lap (passenger posture) and hands-on-the steering wheel (driver posture). The subjects are considered to be sitting with their back supported on a specially designed rigid seat, providing a representative automotive posture with seat pan installed at an angle of 13° with respect to the horizontal and backrest inclined at an angle of 24° with respect to the vertical. Initially, the mean apparent mass response characteristics of the 24 subjects with mass ranging from 48 to 111·4 kg (overall mean body mass of 71·2 kg) are reported for each of the two hand positions. Further analysis is then performed to report the mean apparent mass characteristics of subjects within four different mass ranges: less than 60 kg; between 60·5 and 70·5 kg; between 70·5 and 80 kg; and above 80 kg. These data are thus used to develop and validate automotive body mass dependent models with the structure presented in Figure 1 for postures relating to the two hand positions considered.

4.1. AUTOMOTIVE BASE MODEL PARAMETERS IDENTIFICATION

The corresponding automotive base model parameters are identified from application of the parametric optimization technique defined by equations (9) and (10), with the weighting factors β and ψ_1 and ψ_2 set equal to zero in view of the unavailability of seat-to-head transmissibility data. The contributions due to seat-to-head transmissibility in the minimization function, however, are incorporated within the constraints, by limiting the peak transmissibility to 1·6 in order to ensure feasible solutions of the multi-d.o.f. model structure.

The automotive base model parameters are initially determined on the basis of the mean apparent mass data relating to the 24 subjects for each of the two hand positions considered by minimizing the error between the calculated and mean measured apparent mass response. Furthermore, the number of discrete frequencies N is extended to cover the 0·5 to 40 Hz frequency range, while the weighting factors λ_1 and λ_2 in equation (10) are specifically chosen to enhance the magnitude and phase errors in the vicinity of the resonant frequencies in the 5·0–12·0 Hz range. The resulting minimization problem expressed by equations (1)–(6) and (9)–(11) is solved, with the weighting factors identified above. In the absence of data on seat-to-head transmissibility, a number of constraints are introduced in an effort to limit the number of potential solutions. Since the mean measured data are related to mean body mass of 54·6 kg, supported by the seat, corresponding to a passenger posture with hands-in-lap and 52·4 kg corresponding to a driver posture with hands-on-steering wheel, limit constraints are defined to allow the total mass to vary within a narrow band ($\pm$ 4%), such that

$$52{\cdot}4 \leqslant \sum_{0}^{3} m_i \leqslant 56{\cdot}8 \text{ kg; hands-in-the lap sitting posture,}$$

$$50{\cdot}3 \leqslant \sum_{0}^{3} m_i \leqslant 54{\cdot}5 \text{ kg; hands-on-the steering wheel sitting posture.} \tag{14}$$

The optimization function is further subject to the following parameter constraints:

$$m_0 = 2\,kg; \qquad k_i > 0 \quad \text{and} \quad c_i > 0, \quad i = 1,\ 2, 3 \tag{15}$$

where an equality constraint is imposed on mass m_0 representing the mass in contact with the seat, where the value is selected from the base model parameters discussed in section 2.1. This mass is kept constant to limit the number of masses that would have to be changed to incorporate body mass variation within a potential dummy construction.

Furthermore, an eigenvalue analysis is performed during each iteration to examine the natural frequencies and damping ratios of the model. The modal damping ratios are further constrained to ensure underdamped response of the model, such that

$$\zeta_i \leqslant 0{\cdot}6, \quad i = 1, 2, 3, \tag{16}$$

TABLE 3

Parameters of the automotive base models applicable to seated passengers (hand-in-lap) and drivers (hands-on-steering wheel)

Parameter	Parameter values	
	Hands-in-lap model	Hands-on-steering-wheel model
m_0 (kg)	12·0	2·0
m_1 (kg)	10·3	12·9
m_2 (kg)	16·5	14·1
m_3 (kg)	25·0	23·9
$\sum m_i$	53·8	52·9
k_1 (kN/m)	126·6	136·4
k_2 (kN/m)	600·3	750·4
k_3 (kN/m)	61·3	46·0
c_1 (Ns/m)	2122	1933
c_2 (Ns/m)	899	674
c_3 (Ns/m)	594	742

where ζ_i is the modal damping ratio, where an upper bound of 0·6 is set based on values which are often considered to apply for the dominant first mode in the analysis of biodynamic models.

Although no data are available on seat-to-head transmissibility, a constraint is imposed on the peak acceleration transmissibility of each mass to ensure adequately damped and stable response. The peak acceleration transmissibility was limited to a value of 1·6 on the basis of measured reported data [3], such that

$$\left[\frac{x_1}{x_0}(\omega)\right]_{max}, \quad \left[\frac{x_2}{x_0}(\omega)\right]_{max}, \quad \text{and} \quad \left[\frac{x_3}{x_0}(\omega)\right]_{max} \leqslant 1{\cdot}6. \tag{17}$$

The base model parameters derived while applying the above constrained minimization problem are listed in Table 3 for both automotive seating postures involving hands-in-lap (passenger) and hands-on-steering wheel (driver). The validity of the derived automotive base models, corresponding to the mean biodynamic responses, is further examined by comparing the model responses with the mean measured responses as shown in Figures 7 and 8 for the respective body postures.

The results show very good agreement between the mean measured and base model responses characteristics for both automotive postures. The modulus responses of the base models correlate very well with the mean measured data corresponding to both postures at frequencies below 15 Hz. At higher frequencies, the base model responses, however, deviate slightly from the measured modulus responses owing to the higher weighting selected in the lower frequency range. As for the phase response, more deviation is observed for the posture involving hands on the steering wheel, especially at higher frequencies. The agreement obtained between the base model predictions and the target data is seen to be considerably better when the derivation is performed on the basis of data defined for the automotive posture rather than on the proposed ISO/DIS 5982:2000 [4] data. This is most likely attributed to the relaxed requirement of matching only one response function with a defined upper bound of the other response function over the entire frequency range considered.

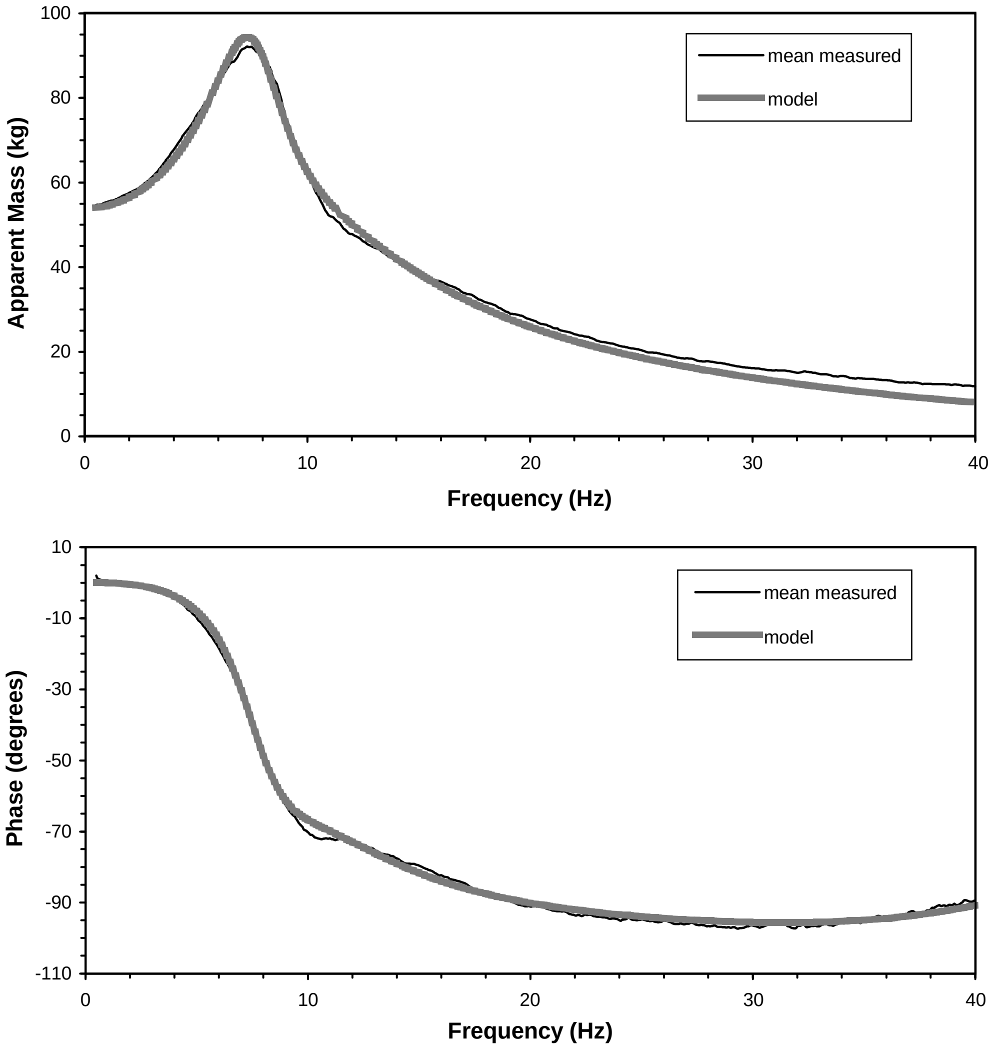

Figure 7. Comparison of the automotive base model predictions of apparent mass, ———; with the mean measured response, ———; applicable to seated automobile passengers with hands-in-lap.

4.2. AUTOMOTIVE MASS-DEPENDENT MODEL DEVELOPMENT AND VALIDATION

In view of the strong dependence of visco-elastic properties of polyurethane foam automotive seats on the seated occupant mass, the realization of body mass dependent models for automotive seat applications is perhaps more important. The proposed methodology is thus applied to identify parameters of the generic automotive mass dependent model for both seating postures: passenger (hands-in-lap) and driver (hands-on-steering wheel). The parameter identification task is performed on the basis of four different target apparent mass data sets reported for four different mean group body masses: below 60 kg, 60·5–70·5 kg, 70·5 to 80 kg and above 80 kg [14]. As before, the stiffness and damping parameters of the model are kept equal to those defined in the automotive base model. While mass m_0 is held constant at 2 kg, the remaining masses m_1, m_2 and m_3 are determined from application of a constraint to ensure that the sum of all the masses lie in the vicinity of

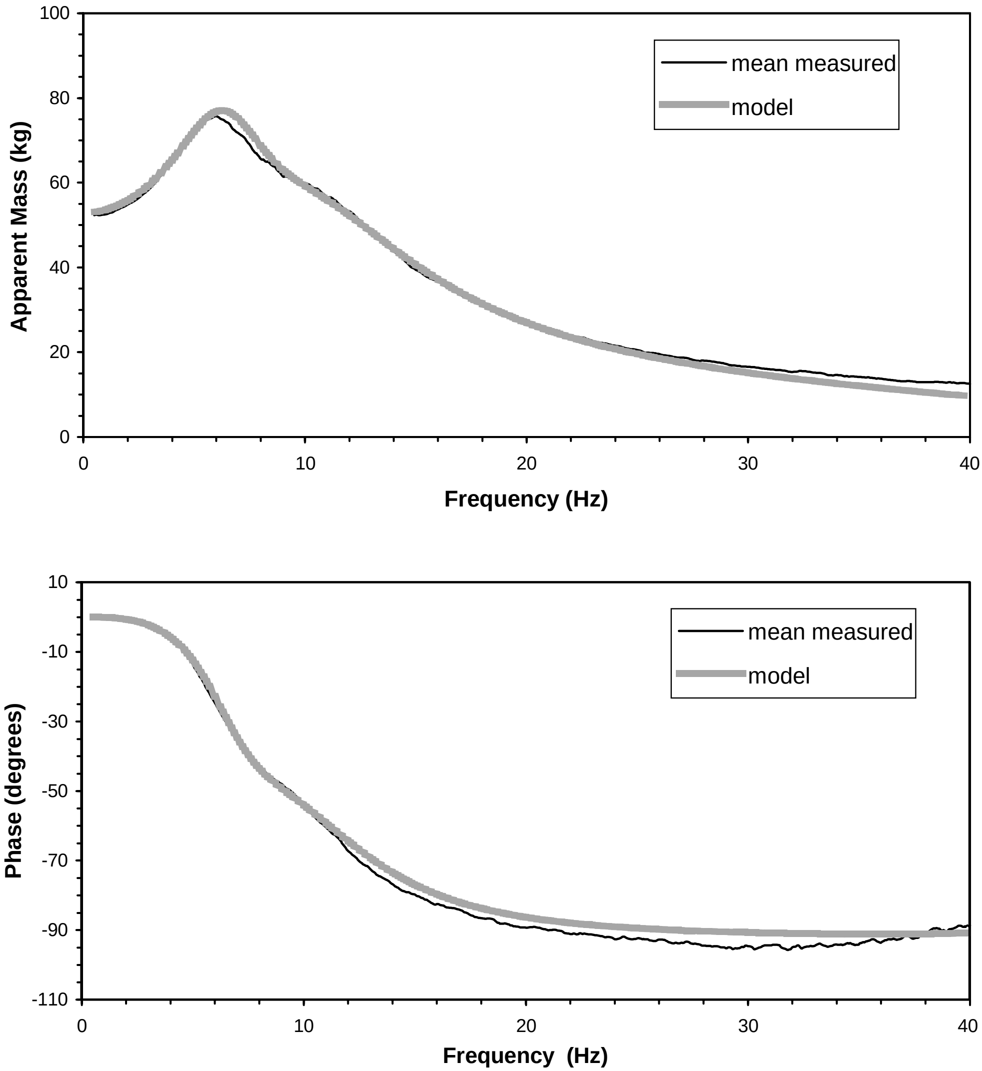

Figure 8. Comparison of the automotive base model predictions of apparent mass, ———; with the mean measured response, ———; applicable to seated automobile drivers with hands-on-steering wheel.

the mean body mass supported by the seat for each occupant mass group. These constraints on the sum of the model masses are expressed in Table 4, which provides the solution of the resulting minimization problems in terms of the four sets of automotive mass dependent model parameters corresponding to each posture.

The results presented in Table 4 indicate that all the model masses, except m_0, increase with the mean group mass, with mass m_3 being the most significant, while the variations in mass m_2 are relatively small. The body mass dependence of the model is thus accounted for mostly by masses m_1 and m_3. While it would have been desirable to limit the mass variation to a single mass m_3 as in section 3, such an approach could not provide a close enough fit with the measured apparent mass responses, especially those relating to the highest and lowest group mass ranges. The accessibility to some data on seat-to-head transmissibility could possibly have permitted the definition of a more appropriate set of base model

TABLE 4

Parameters of the automotive body-mass dependent models applicable to seated passengers (hands-in-lap) and drivers (hands-on-steering wheel)

Posture	Parameter	Mass parameter values (kg) Mass range (kg) < 60	60·5–70	70·5–80	> 80	Mass values Mean response model
Hands-in-lap	m_0	2	2	2	2	2
	m_1	6·7	9·7	13·7	20·0	10·3
	m_2	15·0	16·0	16·1	17·2	16·5
	m_3	18·0	23·4	26·3	30·4	25·0
	$\sum m_i$	41·7	51·1	58·1	69·6	53·8
Hands-on-steering wheel	m_0	2	2	2	2	2
	m_1	10·5	12·5	13·8	20·8	12·9
	m_2	11·0	13·2	14·3	15·0	14·1
	m_3	17·0	22·6	25·4	30·5	23·9
	$\sum m_i$	40·5	50·3	55·5	68·3	52·9

parameters whereby it would have been possible to achieve mass variation through the use of a single mass.

The validity of the automotive mass dependent model is examined by comparing the model response with the mean apparent mass response characteristics of occupants within different mass groups. Figures 9 and 10 illustrate the modulus and phase response characteristics of occupants within different mass groups seated with hands-in-lap and hands-on-steering wheel, respectively, where they are compared with the corresponding mean measured data obtained for respective mass groups. The results show reasonably good agreement between the model and mean measured response characteristics, specifically at frequencies below 10 Hz. Both the proposed automotive mass-dependent model and the mean measured data exhibit a decrease in primary resonant frequency and an increase in the modulus response with increase in the occupant mass. The modulus response of the model corresponding to light weight occupants (mass $\leqslant 60$ kg), however, reveals considerable deviations from the mean measured modulus in the 10·0–15·0 Hz frequency range.

The modulus responses of the automotive mass-dependent model converge to similar values at frequencies above 17 Hz, irrespective of the mass group, while the mean measured data corresponding to different mass groups reveal certain differences at higher frequencies. These discrepancies between the model and measured response at higher frequencies are most likely attributed to emphasized weighting at lower frequencies, non-linear biodynamic behaviour of seated occupants, and equality constraints imposed on the stiffness and damping parameters of the models. The apparent mass phase response characteristics of the passenger and driver mass-dependent models also exhibit reasonably good agreement with the mean measured data in most of the frequency range for all the mass groups, as shown in Figures 9 and 10. For applications in automotive seat testing, the proposed automotive mass dependent models can thus be considered to describe adequately the biodynamic behaviour of occupants of different masses subject to postural and excitation conditions applicable in automobiles.

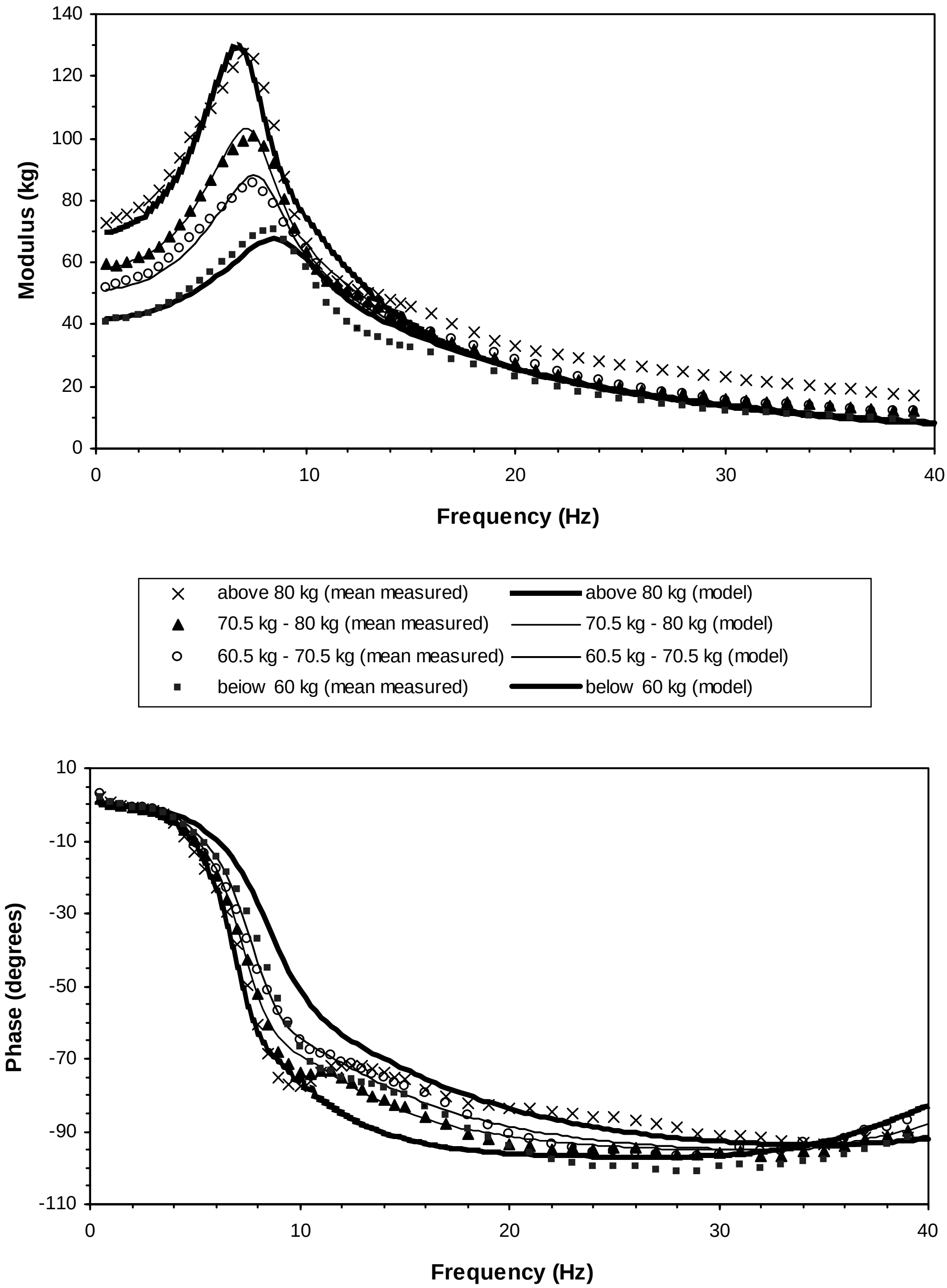

Figure 9. Comparison of the automotive mass-dependent model predictions of apparent mass with the mean measured response reported for automobile passengers (hands-in-lap) with different mass ranges.

5. CONCLUSIONS

A body mass dependent model was derived whose basic structure and base model parameters were determined such as to approximate the mean apparent mass and seat-to-

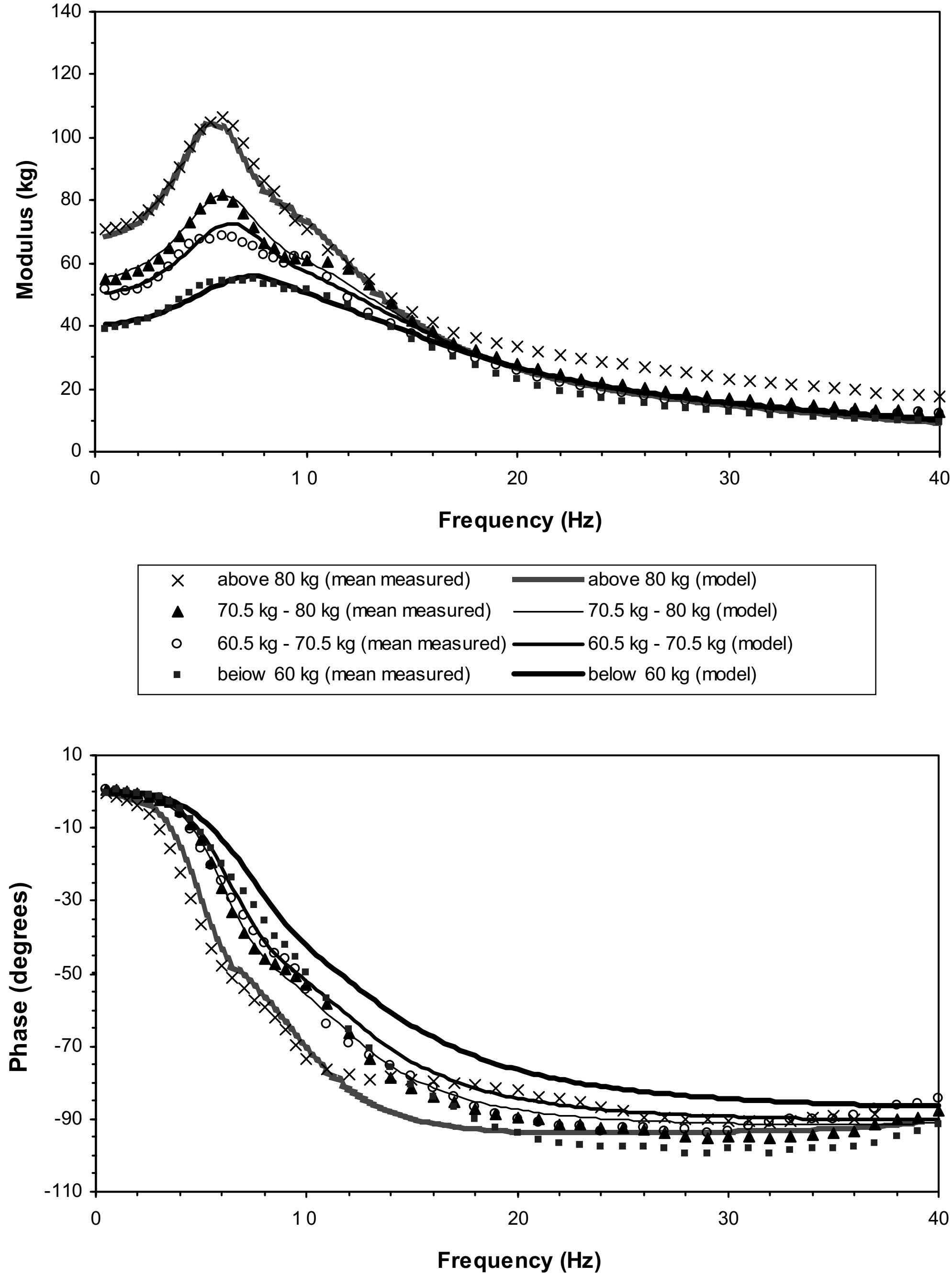

Figure 10. Comparison of the automotive mass-dependent model predictions of apparent mass with the mean measured response reported for automobile drivers (hands-on-steering wheel) with different mass ranges.

head transmissibility responses proposed in ISO/DIS 5982:2000 in the 0·5–20 Hz frequency range for a mean body mass of 75 kg. The requirement imposed on the model to satisfy both simultaneously "to the body" (i.e., apparent mass) and "through the body" (i.e., seat-to-head transmissibility) transfer functions was seen as an advantage to enhance the uniqueness of the model and to ensure that the model parameters could relate more closely to the true dynamic characteristics of the body.

The influence of body mass on the apparent mass and driving-point mechanical impedance characteristics was estimated on the basis of such a model by varying the base model parameters, particularly the masses of the base model, while ensuring that their sum could represent the proportion of body mass expected to lie on the seat for occupants with different weights. For applications to the ISO/DIS 5982:2000 data, only one of the model masses had to be varied to achieve total body masses of 55, 75 and 90 kg. The results of the computations for these various body masses led to apparent mass and driving-point mechanical impedance characteristics which fell reasonably well within the envelopes of the idealized values defined in ISO/DIS 5982:2000. The derived responses at frequencies below 12 Hz for the different body masses showed trends which are in agreement with those reported in the literature, namely that the modulus of the response functions increases with body mass and the peak modulus shifts to lower frequency as the mass increases. However, a direct validation of the derived generic body mass dependent model as applied to the ISO/DIS 5982:2000 data could not be achieved in view of the lack of apparent mass and driving-point mechanical impedance data reported under the required conditions for groups with body masses corresponding to those investigated.

The base model derived in this study was further applied to account for measured apparent mass data applicable to subjects maintaining an automotive seated posture with both hands-in-lap (passengers) and hands-on-steering wheel (drivers). The results obtained in this study have shown that by adapting the parameters of the model derived on the basis of the ISO/DIS 5982:2000 data to fit the apparent mass data reported for automobile occupants within four mass groups: less than 60 kg, 60·5–70·5 kg, 70·5–80 kg and above 80 kg, corresponding mass-dependent models could be derived for both automobile passengers and drivers. A comparison of the apparent mass response of these mass dependent models with the data reported for the different mass ranges have shown that they could account reasonably well for the dynamic behaviour of the occupants at frequencies below 10 Hz, thus suggesting that they could effectively find applications in vibration seat testing to account for the body influence on the seat response.

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