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LINEAR PLANAR MODEL OF SITTING HUMAN BODY SUBJECTED TO VIBRATION IN TWO AXES

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Summary: *A linear four degree-of-freedom (DOF) lumped model with 15 parameters of the human body sitting on a hard seat without a back-rest is developed in the sagittal plane (x-z plane), based on the apparent mass approach. The model is further expanded to a 19 parameters model to account for the interaction of the upper torso with a hard vertical seat back in the lumbar region. Constrained multi-parameter optimisation was performed. The measured data were fitted in the frequency range 0.5-20 Hz. Simple model structures were arrived at to simultaneously approximate measured vertical and fore-and-aft apparent masses. Developed model structures and the identified parameters can be used for further bio-dynamics research and in seating dynamics research.*

1. Introduction

The biodynamic response of human body to vibration and shock is a complex problem that has been the subject of permanent research. The most comprehensive description of all the aspects can be found e.g. in Griffin (1990) and in abridged way in Mansfield (2005). It continues to be challenging to develop a sufficiently accurate but reasonable simple model for the human body in various practical positions, e.g. sitting on a hard support without a back-rest, sitting in a suspended cushioned driver's seat in working environment or in an unsuspended and partially reclined cushioned passenger car seat. Much work on the measurement and modelling of sitting human body response has been done for the vertical (*z*-axis) direction: Fairley & Griffin (1989, 1990), Boileau et al. (2002), Wang et al. (2004). Many researchers have developed mathematical models of the vertical apparent mass of an upright sitting human on a rigid seat. Their approaches may be classified (Rützel et al., 2006):

i. Using a lumped parameters model (a model consisting of a few degrees of freedom (DOFs)) – solely translational (Fairley, 1990; Wei et al., 1998; Rützel et al. (2006) or translational and rotational, e.g. Boileau et al. (2002) or Nawayseh & Griffin (2009).
ii. Using a finite element approach (distributed parameters model), modelling the body in a "sliced" fashion: Kitzaki & Griffin (1997), Pankoke et al. (1998) to name but a few.
iii. Using multi-body approach in the sagittal plane; however, attempting to describe the behaviour of the seated human body in the vertical direction only. This approach is used for the automobile posture (Kim et al., 2003, 2005; Cho & Yoon, 2001; Wang, 2004).

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Few authors were attempting to model the seated human body behaviour in non-vertical directions (Manfield & Lundström, 1999; Fleury & Mistrot, 2006; Stein et al., 2006, 2007). Models were lumped parameters types, consisting of translational DOFs only.

This paper presents reasonable simple mechano-mathematical models that are justified from physical and biodynamical point of view to describe simultaneously the measured apparent mass of the sitting human body in the *z*- and *x*- directions, taking into account the main cross influence from the *z*-direction to the *x*-direction. First a model of the human torso, sitting upright on a hard seat is proposed, further augmented by the interaction with the upright situated hard seat back. Model parameters are identified by multi-criteria constrained optimisation. The latter model uses most of the parameters identified for the first one. In this way the marked effect of the rigid seat back is accounted for.

2. The apparent mass as seated human body dynamics descriptor

The biodynamic response of the seated human body is often been evaluated in terms of the driving point impedance or apparent mass in relation to the force and the acceleration at the interface between subject and the seat, explained in detail in Griffin (1990) and in Mansfield (2005). Both methods indicate the presence of resonances in the human body–seat system. The apparent mass is a well-established descriptor in bio-dynamics and in research of vibration influence on humans (Griffin, 1990; Fairley & Griffin, 1989, 1990; Mansfield, 2005), as well as the ISO standards ISO 5982:1981 and ISO 5982:2001. The current standard ISO 5982:2001 defines the apparent mass $\mathbf{M}_a$ for the vertical direction (*z*-axis). In the same way apparent mass for the fore-and-aft direction (*x*-direction) and for the lateral direction (*y*-direction) are defined. Generally, the apparent mass $\mathbf{M}_a(\omega)$ as a function of positive angular frequency $\omega = 2\pi f$ within a given frequency range is the complex ratio of the force $\mathbf{F}(\omega)$ applied to the system and the resulting motion (acceleration $\mathbf{a}(\omega)$) at the same point and in the same direction, both being complex quantities:

$$\mathbf{M}_a(\omega) = \frac{\mathbf{F}(\omega)}{\mathbf{a}(\omega)}. \tag{1}$$

It is much more practical to generate required acceleration excitation (harmonic or random) and measure the resultant force. So in practice apparent mass is evaluated using this approach.

Some recent papers on measurement and modelling of the vertical direction apparent mass of human body sitting on a rigid seat with or without back support were presented in (Fairley & Griffin, 1989; Griffin, 1990; Nawayseh & Griffin, 2009; Mandapuram et al., 2005; Liang & Chiang, 2008). Fairley's & Griffin's measurements illustrate the non-linear human body response to whole-body vibration and its dependence on multitude of factors that are difficult to control. They illustrate a large inter- and intra- subject variability, as well as marked influence of a rigid seat back standing upright. So the maximum of the apparent mass for one subject shifted from approx. 4.3 Hz for the "normal" position to 7.5 Hz to the position with tensed muscles due to variation in the body tension, while there was virtually no shift for another subject. As the musculature tension is hardly controllable the so caused variability can be accounted for only by taking into account a statistically balanced cohort, i.e. using a median course of apparent masses of a cohort of subjects and perform a sensitivity analysis.

Nawayseh & Griffin (2005a) measured the cross-axis influence of the vertical WBV vibration influence on 12 male seated persons for four different excitation acceleration intensity (Root-Mean-Square (RMS) values: 0.125 m s^{-2}, 0.250 m s^{-2}, 0.625 m s^{-2}, 1.250 m s^{-2}) and four different test person postures on the rigid seat (feet hanging, maximum tight contact, average thigh contact and minimum tight contact). Inter-subject variability was observed, as well as differences due to different sitting postures. The presented courses can be assumed to be validated and usable for modelling purposes, as reported in Nawayesh & Griffin (2009).

Fairley & Griffin (1990) were concerned with the measurement of human body sitting upright on a rigid seat in a well-defined biodynamical position without interaction with controls or the seat back. Few other papers have been concerned with the influence of the seat-back support: Wang et al. (2004), Mandapuram et al. (2005) or Mansfield & Maeda (2007). Authors have generally assumed a rigid, vertical seat-back support without any cushioning. In papers by Wang et al. (2004) and by Mandapuram et al. (2005) the general influence of the back-contact was examined using three different cases, no back contact, back contact with upright standing rigid back support and a backwards reclined rigid back-support in the so-called automobile posture position was thoroughly examined. Recently Subashi et al. (2009) evaluated the subjective and biodynamic responses (apparent mass) under harmonic excitation at four different magnitudes in the fore-and-aft and lateral directions in the frequency range 1.6 Hz to 10 Hz for human test subjects sitting on a rigid seat without a back support. Conclusions were similar to those reported in works quoted above.

Simple mechano-mathematical approach to apparent mass modelling uses *lumped parameters models* of various complexities (various numbers of DOFs) (Wei & Griffin, 1998; Boileau et al., 2002; Nawayseh & Griffin, 2005b, 2009 and Kim et al., 2005). These models are rather simple (consisting of a series combination of small number of DOFs); however, still accounting for the principal resonances of the seated human body. This approach was pursued also in the view to eventually build a mechanical surrogate of the upper body torso for driver's seats tests to make the need for human test subjects obsolete.

Rützel et al. (2006) uses a *modal approach* with a set of independent DOFs in parallel. This mathematical structure, not resembling the human torso, consisted of as many independent DOFs as many resonances were sought to be approximated. By this parallel structure of independent DOFs the mutual interactions between various DOFs were de-coupled. Use of *Finite Elements Method (FEM)* for the modelling purposes was explored, too, e.g. by Kitzaki & Griffin (1997) or Pankoke et al. (1998). Rotational DOFs were introduced in these studies, in contrast to above-described models using only translational DOFs. The introduction of rotational DOFs calls for knowledge of rotational characteristics of human body and its segments, i.e. rotational stiffnesses and dampings; central moments of inertia and locations of centre of gravity (C.G.) of various segments in respect to a stipulated point of rotation, whose determination in reality is a formidable task. Another issue is the modelling of seated human body in a backwards-reclined position (the so-called automobile posture) (Kim et al., 2003; Cho & Yoon, 2003; Rakheja et al., 2002, 2006). In this position the upper torso weight is mostly supported by the reclined seat back and not by the seat cushion. The torso rotational movement, observed at very low frequency, in vicinity of 0.7 Hz, is not marked. As shown in Nawayseh & Griffin (2005b) if the seat back is inclined backwards by more than 10º the upper torso C. G. is moved backwards and the response markedly differs from that one measured for vertical seat-back position.

In the fore-and-aft and lateral directions, little work on apparent mass modelling has been hitherto reported; the exception being probably the work by Mansfield & Lundström (1999). This model is relevant to a test subject sitting upright on a rigid seat without any seat-back support. Various three degree-of-freedom (3 DOF) models were presented with parameters determined from the apparent mass modulus only. The match between the measured and simulated apparent mass phase differs markedly for frequencies larger than 4 Hz. Below this frequency the differences are smaller. Hence, the models can be assumed to reasonably represent the real situation only up to this frequency.

Recently, Fleury & Mistrot (2006) described a fore-and-aft (*x*-direction) human body model using rotary and translatory mechano-mathematical elements. The model accounts well for the principal resonances of the sitting human body: a rocking rotational around some 0.70 Hz and a translational at some 2.25 Hz in accord with Fairley's observations. They used the model to predict the *x*-direction vibration attenuation by a driver's seat equipped with a fore-and-aft suspension system. Stein et al. (2006) described another *x*-direction model of the human body sitting in an upright position with a cushioned seat upper part, using linear translatory mechano-mathematical elements. The back support effectively damps the rotational movement around 0.70 Hz.

All above models account for one direction only. There are currently no reliable models of the human body sitting upright on a rigid support for the sagittal plane, except of some models for the so-called automobile posture, quoted above. As already commented, this posture is quite different from that one observed in the industrial working environment, hence these models are not suitable for the sought purpose.

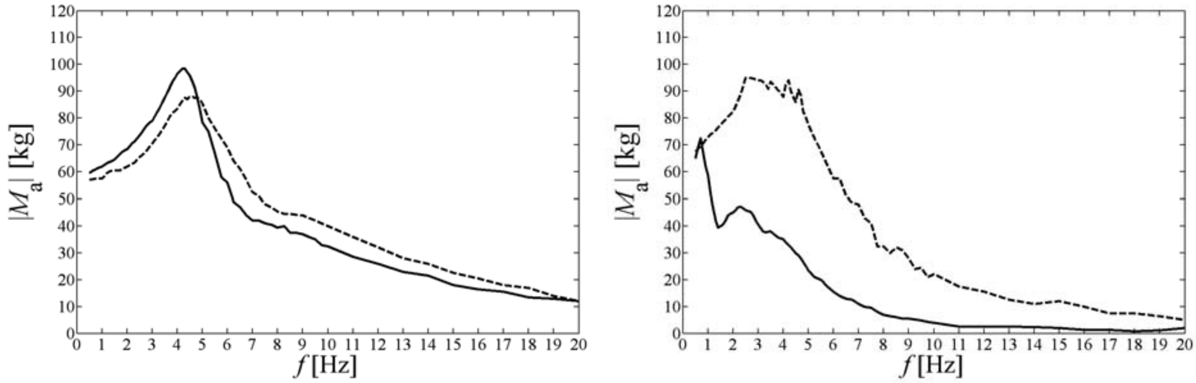
3. Model analysis and parameters identification

The assumptions that form the guidelines for development of the presented model are:

1. The model should be a reasonable simple one; however, accounting for all hitherto known resonances of the human body simultaneously for the *z*- and *x*- directions.
2. The model should be linear one; however, the parameters may be excitation intensity and test subject body mass dependent. Only the most important seated human body dynamic features should be accounted for.
3. No stringent requirements on the model accuracy are to be required. The calculated predictions using the model should be taken as indicative for a mean test subject and the results should be interpreted with some caution.

The data further used for identifying the models parameters are the vertical and horizontal apparent mass data of Fairley & Griffin (1989, 1990) from eight test subjects. The mean apparent mass courses in the frequency range 0.25 Hz to 20 Hz, are reproduced in here as Fig. 1. The experimental data were obtained for excitation intensity of 1.0 m s^{-2}, both in the *z*-axis and *x*-axis directions. The correlation between the force and acceleration measurements was above 0.95, indicating a good linearity and signal-to-noise ratio. Characteristic values, in particular the damped natural frequencies, are given in the upper part of Table 1.

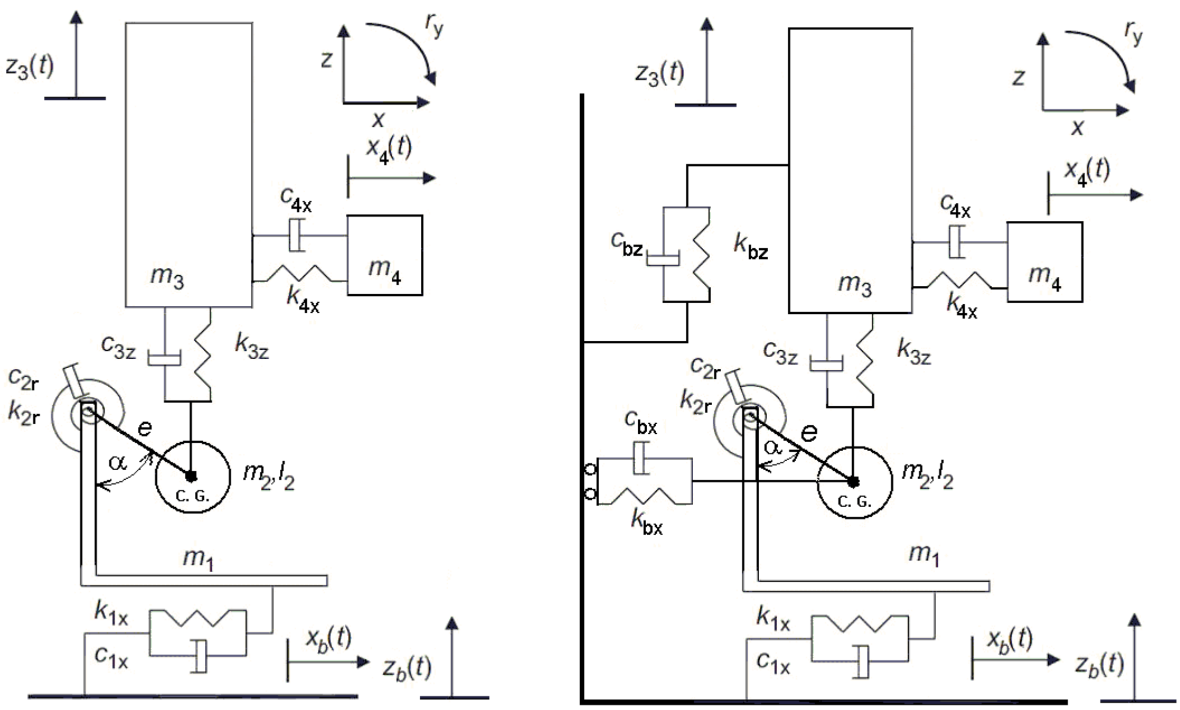
From Fig. 1 it can be seen, that by introduction of the seat-back there is no substantial difference in the apparent mass in the *z*-direction; whereas there is a rather marked difference in the performance in the *x*-direction: the peak around 0.70 Hz, attributed to the rotary movement of the upper torso, vanishes; whereas the second peak is more pronounced and spreads-out across a broader frequency band. Hence a different model structure would be required to describe seated driver – seat-back situation in comparison with no-back situation.



(a) (b)

Figure 1. Apparent mass modulus (Fairley & Griffin, 1989, 1990): (a) vertical direction; (b) fore-and-aft direction: without backrest (——), with backrest (– – –).

In analogy to studies on human body model development by Stein et al. (2006, 2007) it is hypothesised that the mean *human upper torso model can be considered as a lumped parameter linear model* without going into detailed description of various human body segments. The basis of further deliberations is the model of Nawayseh & Griffin (2009) pertinent to excitation in the vertical (*z*-axis) direction. The proposed model of the human body sitting upright on a hard seat is depicted in Fig. 2. It is assumed that the test subjects sat in a well defined position with upper legs in horizontal, lower legs vertical and the feet supported by a horizontal support, vibrating synchronously with the rigid seat.



(a) (b)

Figure 2. Lumped parameter model for the seated human body: (a) without the seat back, (b) with the seat-back, both accounting for the *z*-axis and *x*-axis dynamic properties.

Similar nomenclature as used by Nawayseh & Griffin (2009) will be used throughout:

e is distance of C. G. of mass m_2 from point of rotation at mass m_1,

I_2 is the moment of inertia of mass m_2 about its C. G.,

J_2 is the moment of inertia of mass 2 about the point of rotation ($J_2 = m_2e^2 + I_2$),

k_{1x} and c_{1x} are the fore-and-aft stiffness and damping beneath the mass 1,

k_{2r} and c_{2r} are the rotational stiffness and damping of mass 2,

k_{3z} and c_{3z} are the vertical stiffness and damping beneath mass 3,

k_{4x} and c_{4x} are horizontal stiffness and damping of mass 4, representing the viscera,

m_1, m_2, m_3, m_4 are the masses of mass from 1 to 4,

$x_b(t)$ is the fore-and-aft displacement of the base,

$x_1(t)$ is the fore-and-aft displacement of the mass m_1, representing the buttocks,

$x_4(t)$ is the fore-and-aft displacement of the mass m_4, representing the viscera,

$z_b(t)$ is the vertical displacement of the base,

$z_3(t)$ is the vertical displacement of mass 3, representing the back,

α is the angle that eccentricity e has in respect to the horizontal in equilibrium,

$\theta(t)$ is the angle of rotation of mass 2.

It should be noted, that mass m_3 is moving just vertically (despite the rotational movement of mass m_2), while horizontal DOF made of k_{1x} and c_{1x} moves only horizontally (Fig. 2(a)).

The model accounting for the interaction with the seat back is constructed from the above one by introducing two constraining bonds, denoted by index “b” for back (see Fig. 2(b)):

i. An x-direction DOF damping the rotary movement of the mass m_2, representing a back support in the lumbar region (k_{bx}, c_{bx}). In the z-direction this DOF is allowed to move;

ii. A z-direction DOF, which damps the vertical movement of mass m_3 representing a shear movement of the upper back in respect to the seat back (k_{bz}, c_{bz}).

The optimisation procedure for both models is the same as used in previous author’s papers. The apparent mass data were digitised from courses of Fig. 1 in the frequency domain between 0.5 Hz and 20 Hz. At each frequency f_i the difference d_i between the simulated $\mathbf{M}_{aSi}$ and measured apparent mass $\mathbf{M}_{aMi}$ magnitudes was calculated. The standard least squares method was used to minimize the objective function QE, being the sum of squares of distances d_i:

$$\mathrm{QE_Z} = \frac{1}{N}\sum_{i=1}^{N} d_{Zi}^{\;2} = \frac{1}{N}\sum_{i=1}^{N}\left(\mathbf{M}_{\mathrm{aSZ}_i} - \mathbf{M}_{\mathrm{aMZ}_i}\right)^2 \Rightarrow \min; \tag{2a}$$

$$\mathrm{QE_X} = \frac{1}{N}\sum_{i=1}^{N} d_{Xi}^{\;2} = \frac{1}{N}\sum_{i=1}^{N}\left(\mathbf{M}_{\mathrm{aSX}_i} - \mathbf{M}_{\mathrm{aMX}_i}\right)^2 \Rightarrow \min. \tag{2b}$$

The standard error ε_{aj} ($\varepsilon_{aj} = \sqrt{\mathrm{QE_j}}$) of the simulated apparent mass $\mathbf{M}_{aSj}(\omega)$ allows assessment of goodness of fit in the same mass units as the measured variable $\mathbf{M}_{aMj}(\omega)$ for index j = X or Z for the direction. A relative error measure $\mathrm{RE_{avgj}}$ was introduced too:

$$\mathrm{RE_{avgj}} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\mathbf{M}_{\mathrm{aMj}_i} - \mathbf{M}_{\mathrm{aSj}_i}}{\mathbf{M}_{\mathrm{aSj}_i}}\right| \times 100\ [\%]. \tag{3}$$

The *MATLAB*® function *fminsearch* from the Optimisation Toolbox® was used based on the Nelder and Mead simplex algorithm. The function was modified to facilitate constrained optimisation, i.e. limiting the search to a parameters subspace representing physically meaningful values (positive masses and stiffnesses). The numerical value of $\mathbf{M}_{aSj}(f_i)$ for each frequency f_i was calculated using formulas for the apparent mass $\mathbf{M}_{aMj}$, which were derived from the equations describing the respective mechano-mathematical model. The frequency range of the identification was chosen between 0.5 Hz and 20 Hz. Different discrete frequency levels for identification were chosen: in the frequency interval 0.5 to 5 Hz the step was 0.1 Hz; in the interval 5.25 Hz to 10 Hz the step was 0.5 Hz, between 10 Hz and 20 Hz 1 Hz step was deemed as sufficient, because no marked resonance phenomena were expected. Same initial conditions for start of the identification procedure were used in accord with the mean parameters identified for the vertical direction by Nawayseh & Griffin (2009). The dependence of the optimisation on the initial parameters implies that the solutions obtained may not be unique. No global minimum in the 15-dimensional (or 19-dimensional) parameters space could be found, but just a local minimum. The models are constructed from data obtained for excitation intensity of 1 m s^{-2} and are valid for this excitation level only.

5. Identification of apparent mass models parameters

First the simulated courses are compared with those of the experimentally determined apparent mass courses: in Fig. 3(a) for the z-direction and in Figs. 3(b) and 3(c) for the x-direction. The calculated damped natural frequencies f_{dj} and simulated and measured apparent masses magnitudes, M_{aSj} and M_{aMj}, respectively at 0.5 Hz, representing the quasi-static mass of the sitting person acting onto the hard seat are presented in the second part Table 1. The most important damped natural frequencies f_{dj} of the model are denoted in bold. Identification was performed independently for each axis. Two different results for the x-axis, albeit with different accuracy, are presented, illustrating the non-uniqueness of the identification; the second one is sub-optimal.

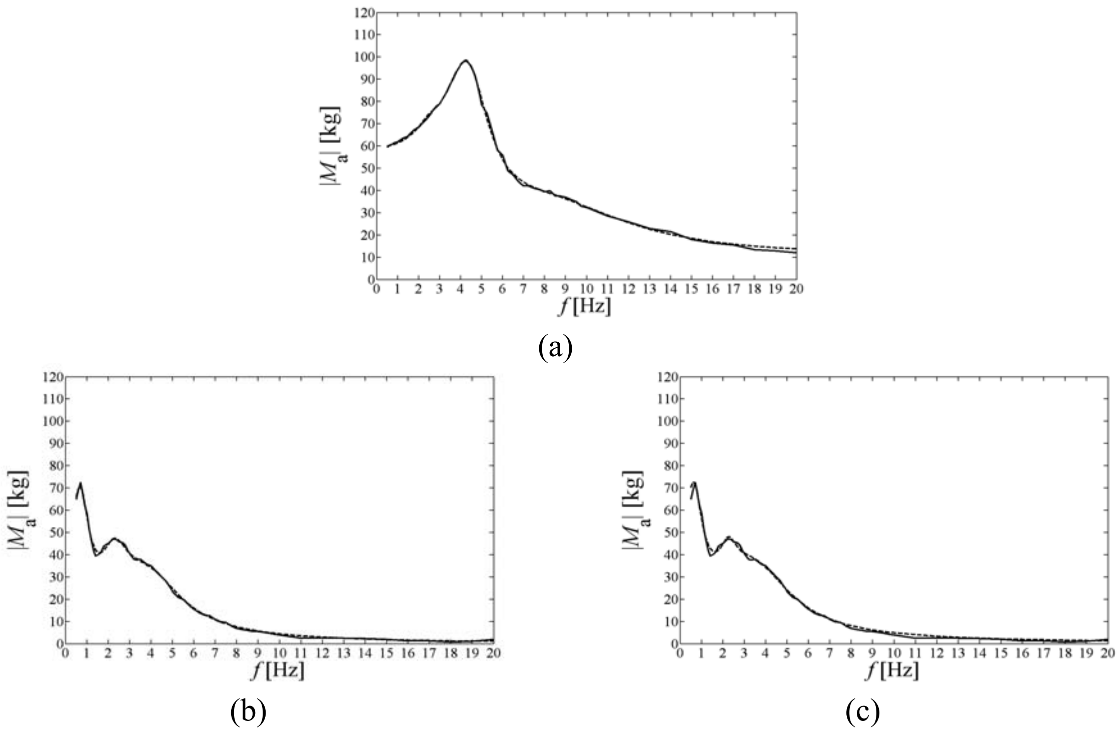


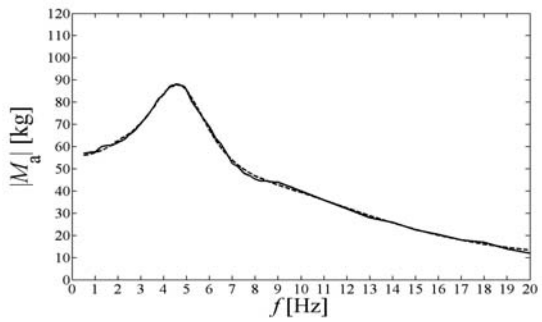
Figure 3. Measured (——) and identified (– – –) apparent masses without the seat-back: (a) for the z-direction, m_1 = 0 kg; for the x-direction (b) m_1 = 0 kg, (c) m_1 = 3.5 kg.

Table 1. Characteristic values of experimentally determined and simulated apparent masses.

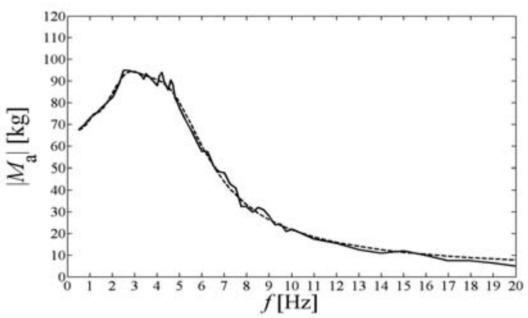
	Figure	Conditions	M_{aM} [kg]	M_{aS} [kg]	f_d [Hz]			RE_{avg} [%]	
MEAS	Fig. 1(a)	z-dir, back-off	59.5	—	—	4.25	—	—	—
	Fig. 1(a)	z-dir, back-on	57.0	—	1.30	—	4.60	—	—
	Fig. 1(b)	x-dir, back-off	65.0	—	0.70	2.25	3.50	—	—
	Fig. 1(b)	x-dir, back-on	67.5	—	2.70	2.70	4.30	—	—
SIM	Fig. 3(a)	z-dir, back-off	59.5	60.0	1.20	2.57	3.32	0.84	1.5
	Fig. 3(b)	x-dir, back-off	65.0	65.9	0.70	2.11	2.13	0.84	5.4
	Fig. 3(c)	x-dir, back-off	65.0	70.2	0.63	2.23	2.28	1.25	7.3
	Fig. 4(a)	z-dir, back-on	57.0	56.2	—	2.06	4.93	0.81	1.4
	Fig. 4(b)	x-dir, back-on	67.5	67.3	1.29	2.64	4.87	1.77	3.9
	Fig. 4(c)	x-dir, back-on	67.5	66.6	1.83	2.30	4.71	1.97	4.2
	Fig. 5(a)	z-dir, back-on	57.0	60.0	1.21	1.68	4.57	2.62	4.9
	Fig. 5(b)	x-dir, back-on	67.5	64.3	2.23	2.80	3.68	2.13	3.6

Note a reasonable approximation of the course determined experimentally and the identified one, indicated by reasonable values of the error variables ε_{aj} and RE_{avgj}, especially for the z-direction. However, for each axis a different set of parameters was obtained.

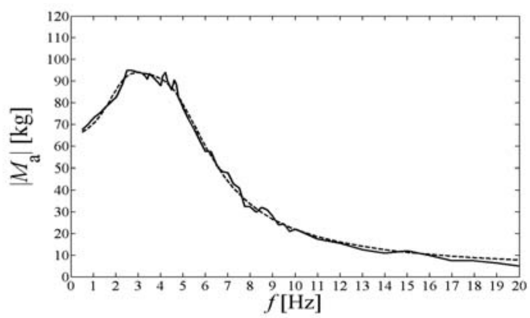
The same approach was followed with the data gathered while the test subjects were supported by a vertically situated seat-back. The apparent mass courses are presented for the z-direction in Fig. 4(a) and for the x-direction in Fig. 4(b) and 4(c). All 19 parameters but m_1, were allowed to change. For the x-axis the parameter m_1 was set deliberately once to zero (Fig. 4(a)) and to m_1 = 3.5 kg (Fig. 4(b)). Both approaches furnish results with reasonable fit.



(a)



(b)



(c)

Figure 4. Measured (——) and identified (– – –) apparent masses for the back-on situation: (a) z-direction, m_1 = 0 kg; x-direction: (b) for m_1 = 0 kg; (c) for m_1 = 3.5 kg.

6. Constrained apparent mass models parameters identification

By the above procedure sets of 14 parameters was obtained for the no-back situation: one for the *z*-direction and another one for the *x*-direction. In the same way two different sets of 18 parameters for the back-on situation were obtained, stipulating a fixed value for parameter $m_1 = 0$. However, the aim is to arrive at a much smaller set of parameters, which would be acceptable in view of limited accuracy and still usable for indicative predictions. Specifically following hypothesis was tested:

A/ Using a sub-set out of the identified set of 14 parameters for the no-back situation as the basis for identification of the parameters of the back-on situation for the *z*-direction.

B/ Using a sub-set out of the identified set of 14 parameters for the no-back situation as the basis for identification of the parameters of the back-on situation for the *x*-direction.

From bio-dynamical point of view this approach aims at using as much of the parameters of the human body sitting upright on the hard back for the situation when it has the back supported by an upright standing rigid seat-back. The assumption is that only some bio-dynamic properties of the human body change when the seat-back is used. The result for the *z*-direction is presented in Fig. 5(a), using the same approach as above. The identified parameters are condensed in Table 2, the respective error variables in Table 1. Those in common with the no-back situation, depicted in Fig. 3(a), are denoted in bold.

The analysis in the *x*-direction was performed starting with the same premises and the same approach, using $m_1 = 0$; however, the approach turned out to be futile, already for the first step (all masses m_i same) the error variables grew above acceptable values. However, after some test it was found that when the mass m_1 is increased to 3.5 kg a good compliance between the experimentally determined apparent mass curve and the simulated one could be obtained as seen in Fig. 5(b). It was assumed, that the mass m_1 could incorporate a reduced mass of the seat-back, whose influence ought to be manifest in the *x*-direction. The corresponding no-back situation is depicted in Fig. 3(c) above. Identified parameters are condensed in Table 2. Those in common for both Fig. 3(c) and 5(b) are denoted in bold. The k_{bz}, c_{bz} parameters (in italic) could be directly transposed from the *z*-direction.

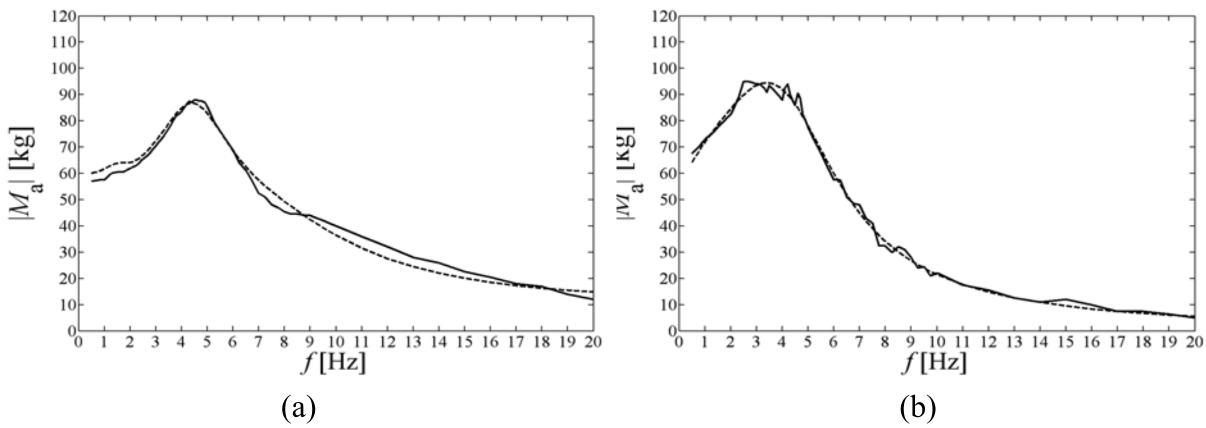


Figure 5. Measured (——) and identified (– – –) apparent masses for constrained back-on situation: (a) for the *z*-direction, (b) for the *x*-direction.

Table 2. Identified apparent mass models parameters for various situations, as depicted in respective figures (parameter dimensions are: m_i [kg], J [kg m^2], e [m], α [rad], k_i [N/m], c_i [Ns/m], ε_a [kg], and RE_{avg} [%]).

conditions	Fig.	m_1	m_2	m_3	m_4	J_{2r}	e	α	k_{1x}	c_{1x}	k_{2r}	c_{2r}	k_{3z}	c_{3z}	k_{4x}	c_{4x}	k_{bz}	c_{bz}	k_{bx}	c_{bx}
***z*-dir, back-off**	3(a)	**0**	**14.9**	**39.9**	**4.7**	**0.16**	**0.152**	**1.802**	**20403**	**575**	**124**	**2.4**	**54176**	**562**	**300**	**24**	—	—	—	—
***z*-dir, back-on**	4(a)	0	12.8	39.5	3.5	0.19	0.210	1.359	11300	534	159	4.3	78498	295	0.1	36	61	19.2	203	35
***z*-dir, back-on**	5(a)	**0**	**14.9**	**39.9**	**4.7**	**0.16**	**0.152**	**1.802**	**20403**	**575**	**124**	**2.4**	**54176**	**562**	**300**	**24**	***4445***	***160***	3972	0.0
***x*-dir, back-off**	3(b)	0	16.9	34.7	1.6	0.54	0.259	1.733	14119	70	16	3.2	7056	299	63	42	—	—	—	—
***x*-dir, back-off**	3(c)	0	**10.6**	**41.4**	**4.0**	0.23	0.262	1.630	**14807**	**118**	5.5	1.2	**9311**	**238**	**1404**	**99**	—	—	—	—
***x*-dir, back-on**	4(b)	0	12.3	46.5	7.2	0.34	0.177	1.050	48529	849	85	1.4	4425	369	7.4	272	64	4.6	26	3.0
***x*-dir, back-on**	4(c)	3.5	6.6	42.8	12.2	0.37	0.201	1.546	49544	840	24	11.1	5626	1.0	3517	219	1.4	0.6	157	22
***x*-dir, back-on**	5(b)	3.5	**10.6**	**41.4**	**4.0**	0.15	0.267	1.571	**14807**	**118**	22	11.4	**9311**	**238**	**1404**	**99**	***4445***	***160***	0.1	226

7. Conclusion

Based on the error variables and the courses of the simulated apparent masses it is seen from Fig. 5(a) that for the *z*-direction the approach using upper torso parameters *and* rotational DOF parameters same as for the no-back situation suits the experimentally determined apparent mass for the back-on situation. This allows for *transposition of up to 15 parameters* from the no-back situation to the back-on situation. So just parameters responsible for the interaction with the rigid seat-back have to be added.

Based on the error variables and the courses of the simulated apparent masses it is seen from Fig. 5(b) that for the *x*-direction same upper torso parameters could be used both for the no-back situation and for the back-on situation. *Up to 9 parameters are in common and could be transposed from the back-off model.* Note that all rotational DOF parameters are different for the back-on situation in respect to back-off situation, as expected. This is so, because the rotational DOF has to accommodate the attenuation of the rotation at 0.7 Hz, which can be achieved only by change in the pertinent parameters and accounting for the seat-back mass. Same values of parameters k_{bz}, c_{bz} for the *x*-axis and *z*-axis could be directly used, indicating that they do not influence the behaviour in the *x*-direction.

The identified angle $\alpha = 1.802$ rad is approx. 103 deg for the *z*-direction, indicating that the upper torso part is oscillating vertically located behind the point of rotation. For the *x*-direction the identified angle $\alpha = 1.571$ for the seat-back situation is exactly 90 deg; whereas for the back-of situation is $\alpha = 1.630$ rad, i.e. 93.4 deg.

If a mechanical simplification of the devised model would be desirable, the identification results could be interpreted as having the pelvis and adjacent vertebral elements rotating on a hinge made of the two hips. The hinge may be associated with lumbar region of the spine.

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