Comfort analysis of car occupants: comparison between multibody and finite element models

E. Pennestrì, P.P. Valentini* and L. Vita

Department of Mechanical Engineering,
University of Rome Tor Vergata,
via del Politecnico, 1 00133 Rome, Italy
E-mail: valentini@ing.uniroma2.it E-mail: pennestri@mec.uniroma2.it
E-mail: vita@ing.uniroma2.it
*Corresponding author

Abstract: This paper deals with numerical models developed in order to simulate the vibrational and postural comfort of car occupants. The proposed models have been based on different mathematical approaches: the first is a multibody dynamics model and the second is a finite elements model. Both models have been validated by means of static and dynamic experimental tests on vehicles using appropriate test rigs. The authors focus on the advantages and disadvantages of each model in order to have useful information about which approach has to be used to predict objectively the comfort of driver and passengers.

Keywords: multibody; FEM; comfort; virtual dummy.

Reference to this paper should be made as follows: Pennestrì, E., Valentini, P.P. and Vita, L. (2005) 'Comfort analysis of car occupants: comparison between multibody and finite element models', *Int. J. Vehicle Systems Modelling and Testing*, Vol. 1, Nos. 1/2/3, pp.68–78.

Biographical notes: E. Pennestrì is a Professor of Applied Mechanics. He received the Laurea in Mechanical Engineering from the University of Rome La Sapienza in 1980, his Master of Science Degree from Columbia University in 1987 and his Doctor of Engineering Sciences degree from Columbia University in 1991. His research interests include kinematics and multibody dynamics.

P.P. Valentini graduated in 2000 in Mechanical Engineering from the University of Rome Tor Vergata, In 2004 he received the Doctoral Degree (PhD) in Design of Mechanical Systems. He is currently a Researcher at the same University and his main fields of interests are modelling of mechanical systems, computer aided design and biomechanics.

L. Vita graduated in 2001 in Mechanical Engineering from the University of Tor Vergata, In 2005 he received the Doctoral Degree (PhD) in Design of Mechanical Systems. He is a Post Doctoral Fellow at University of Rome Tor Vergata. His fields of interests are multibody dynamics simulation methods, vibrational comfort analysis of vehicle passengers.

1 Introduction and background

Occupant comfort is obviously one of the most important goals to achieve during the design of a vehicle. The concept of comfort is very subjective, and a solution which seems comfortable to one may not be comfortable to another.

In general, we can distinguish between three types of comfort.

- Static or postural comfort is the one perceived when sitting. This depends on the shape, the material and the position of the seat and backrest.
- Vibrational comfort which is the one perceived while driving. It depends also on the chassis, suspensions system, tyre and steering system, apart from the same features pointed out in the previous item.
- Acoustic comfort depends on the chassis shape and materials which affect acoustic isolation.
- Quality perceiving is the concept of comfort perceived by the visual and tactile inputs and it depends on the exterior quality, finishing and material of the dashboard and car interiors.

In this paper, just the first two aspects will be investigated.

As concerns the vibrational comfort analysis there are some international standards which define how to evaluate the whole body vibration and the comfort in an objective manner. The basic idea is to monitor the vibrational inputs at many locations of the body taking into account the three most important aspects of the signal: the duration of exposure, its amplitude and the frequencies of the spectrum. In a road vehicle the vibrational inputs come from the road to the chassis (and so to the seat), to the steering wheel and to the pedals.

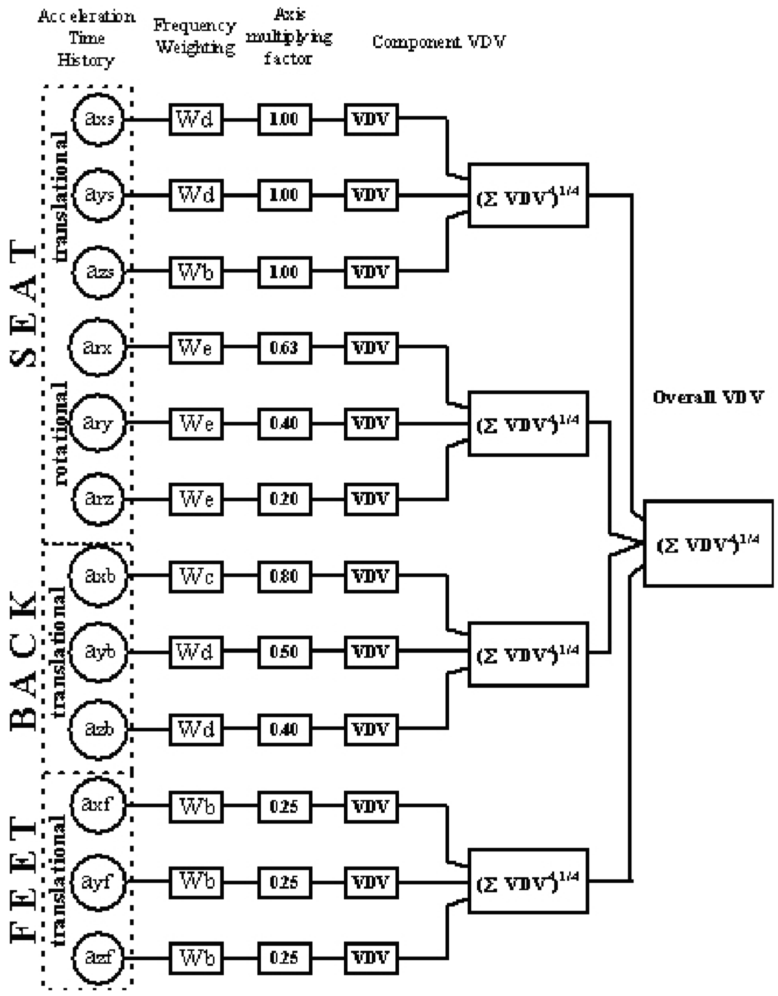
According to many authors (e.g., Griffin (1990)), a more accurate assessment of vibrational exposure is suggested by the British Standard 6841 (1987). The index to be computed is the vibration dose value (VDV) which can be calculated using the following expression:

$$VDV = \left(\int_0^T a_w^4 \mathrm{d}t \right)^{1/4}. \tag{1}$$

Equation (1) states that the VDV is the fourth root of the integral sum of the fourth power of the frequency weighted acceleration time-history a_w all over the period of exposure T. The standard suggests three main locations of acceleration measurement (i.e., feet, back and seat) and the axes direction for an overall amount of twelve acquisitions.

The vibrational comfort is assessed checking that the overall VDV does not reach a critical threshold value. The computational scheme is reported in Figure 1 and measurement points location is presented in Figure 2 (on the left). More details about this threshold value, the measurement points and the frequency weight functions can be found in Griffin (1990) and Valentini and Vita (2003).

Figure 1 VDV computational scheme



The assessment of postural comfort is more difficult. In general it could be said that a seating solution/posture is comfortable when the contact pressure is as uniform as possible and does not have any local peaks. The pressure is measured at the body/cushion interface.

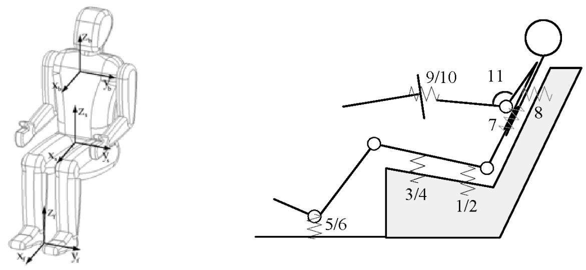
Although in literature, many models have been presented (e.g., Vibration Injury Network, 2001; King, 1984), in this paper a multibody model and a finite element model will be discussed and compared.

2 Multibody model

The proposed multibody model (named DAViD, acronym of Dynamic Automotive Virtual Dummy) is made of 15 rigid elements, 12 of which define the dummy, and 3 describe the car environment. The simulated occupant is composed of two feet, two legs, two thighs, the pelvis, two arms, two forearms, and an upper part that is formed by head, neck, shoulders and chest, rigidly connected together. The remaining bodies included in the model are seat, pedals and steering wheel. In order to represent the human body joints, kinematics constraints and spring-damper elements are used to connect each part of the dummy. In particular, there are two spherical joints between pelvis and thighs, two revolute joints with transverse axes between thighs and legs, two revolute joints with transverse axes between legs and feet, one prismatic joint with longitudinal axis between pelvis and upper part, two spherical joints between upper part and arms, two revolute joints with transverse axes between arms and forearms. The spring-damper elements used in the dummy are one translational, between pelvis and the upper part that represent the stiffness of torso, and two rotational spring-damper elements, between arm and forearm to reproduce the muscular elasticity of the elbow.

The dummy interacts with the car environment by means of seat, pedal and steering wheel contact simulated by other nonlinear spring-damper elements (Figure 2, on the right). The values of stiffness and damping of these elements have been chosen according to the results of compression tests on cushions. Polyurethane foam shows nonlinearity as regards both preload and vibrational frequencies (Valentini and Vita, 2003). The contacts between hand steering wheel and feet platform car are simulated with four very stiff springs (Amirouche et al., 1994).

Figure 2 Body measurement points according to B.S. 6841 and spring damper elements



Since the model is interlaced with an anthropometrical database, geometry, mass properties and spring locations are automatically adjusted by changing only two parameters (i.e., weight percentile and height percentile). It is also possible to modify the backrest inclination and the hip-heel vertical position in order to change the configuration of the seat. The code can also manage simultaneously several acceleration input points. It can receive as input acceleration time histories, acquired by experimental tests, as well as time histories of velocities and positions. Signals can be filtered in order to suppress noise. When required, forces and torques could be introduced as well as other driving constraints.

The equations of motion (Haug, 1988) are deduced in the form of differential algebraic system of index 3 (Hairer and Wanner, 1996) (i.e., constraints on positions):

$$\begin{cases} [M]\{\ddot{q}\}+[\Psi_q]^T\{\lambda\}=\{F_e\} \\ \qquad \{\Psi\}=\{0\} \end{cases} \tag{2}$$

where $[M]$ is the global mass matrix, $\{\Psi\}$ is the vector of constraint equation, $\{\lambda\}$ is the vector of Lagrange's multipliers; $\{F_e\}$ is the vector of external forces; $\{q\}$ is the vector of generalised coordinates. The complete model has 15 bodies which lead to 105 generalised coordinates (in fact each body is described by seven variables, three for the position of the centre of mass and four Euler's parameters to describe the attitude) and 24 d.o.f. Other details about the model can be found in Valentini and Vita (2002, 2003) and Campanile et al. (2001).

3 Finite element model

The proposed FEM is based on the model of half a body (see Figure 3) and it is made up of six bodies for the occupant (the head, the upper part, an arm, a forearm, a thigh, a leg and a foot) and two bodies for car environment (the seat and the steering wheel). The crucial point of the model is the contact between the thigh and the seat. For this reason the mesh generation has been optimised (see Figure 4). First of all the cushion has been discretised with hexahedral solid elements and a nonlinear material property has been defined in order to reproduce the polyurethane foam characteristic (see Figure 5) (Kubo et al., 2000).

Figure 3 The CAD geometry and finite element mesh

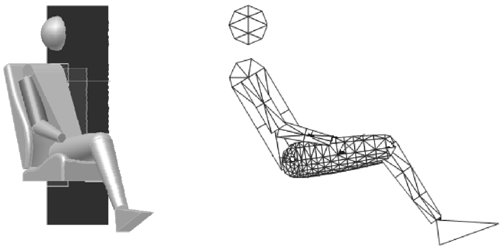


Figure 4 Cushion and thigh mesh

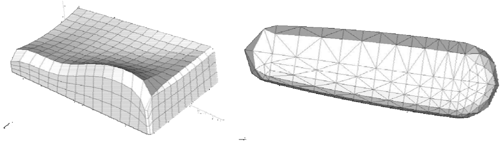
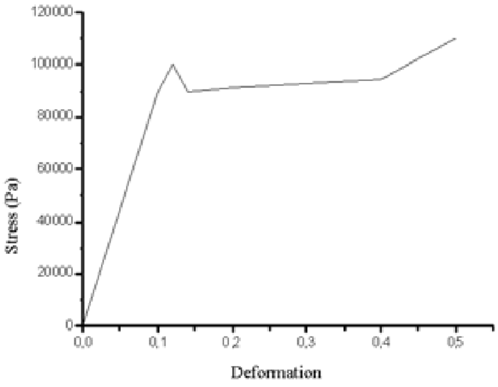


Figure 5 Polyurethane foam elastic property



The thigh has been modelled as a double material solid. The inner part (the bone) has been considered as a rigid bar rigidly connected to other segments, while the external one has been considered deformable as an isotropic material. The values in Table 1 are mean values among those of soft tissue, passive muscles and activated muscles.

Table 1 Soft tissue mechanical properties

Property	*Value*
Young's modulus	$E = 7.5 \times 10^3$ Pa
Poisson's coefficient	$\nu = 0.3$
Density	$\rho = 1000$ kg/m^3

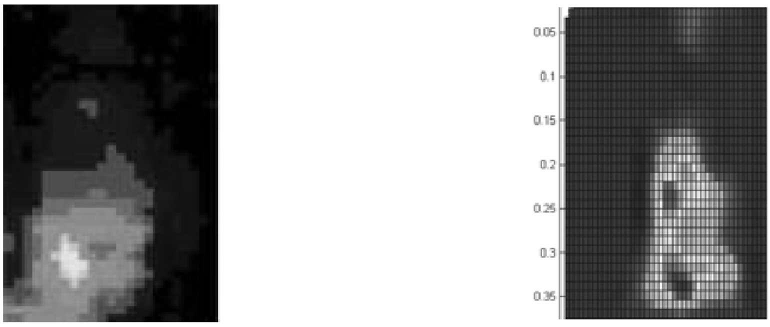
The other body parts have been modelled with a coarser mesh and constrained with the same joints as the multibody model in order to reproduce the correct kinematics (Zatsiorsky, 1998). Moreover the contact between the back and the backrest, the foot and the pedals, the hand and the steering wheel have been modelled using lumped spring-damper elements with the same stiffness and damping coefficients as the multibody model.

4 Experimental tests and validation

The two described models have been validated by means of two experimental campaigns. The first has been performed to check the finite element model and postural pressures. For this reason a group of ten people were seated on a car seat equipped with pressure mats with many transducers (see Figure 6). An example of the comparison between numerical and experimental results is depicted in Figure 7. Although there is not a perfect agreement between the shapes of the simulated and measured pressure field, relevant parameters such as peak location and maximum pressure values are very close.

Figure 6 Pressure mats placed on the investigated seat cushion

Figure 7 Measured pressure field (on the left) and numerical simulation results (on the right)



The difference between the shapes of pressure fields can be explained observing its dependence on the anthropometrical features, which could be summarised in shape and bulk, of the seated occupant. Our present goal is not to mimic faithfully, the actual pressure field, but to predict pressure concentration and this information can be correctly carried out from the model.

The experimental tests to validate the multibody model have been performed using a 4 axes-shaker test rig on which the vehicle has been mounted. The chassis motion was monitored with several accelerometers (see Figure 8) in order to acquire the acceleration signal in many measurement points. Moreover two three axial SAE plate accelerometers have been also placed at the interface between body and both seat cushion and backrest. Other accelerometers have been located at the steering wheel, at the pedals and at the anchor points of the seat in order to measure all the vibrational inputs for the occupant's body. The acceleration Fast Fourier Transform (FFT) of several body locations has been compared to that coming from the simulation using the same vibrational inputs (Figure 9). The frequency response is one of the more interesting indices to evaluate the vibrational comfort (Wu et al., 1999; Gu, 1988; Kirchknopf et al., 1995; Gonçalves and Ambròsio, 2003).

Figure 8 Accelerometer locations on the investigated car

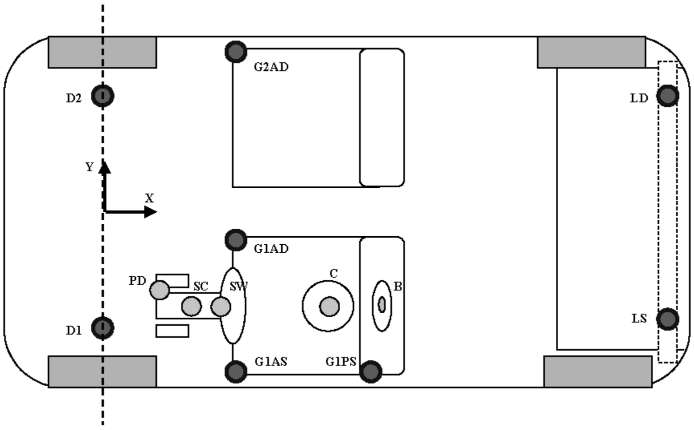
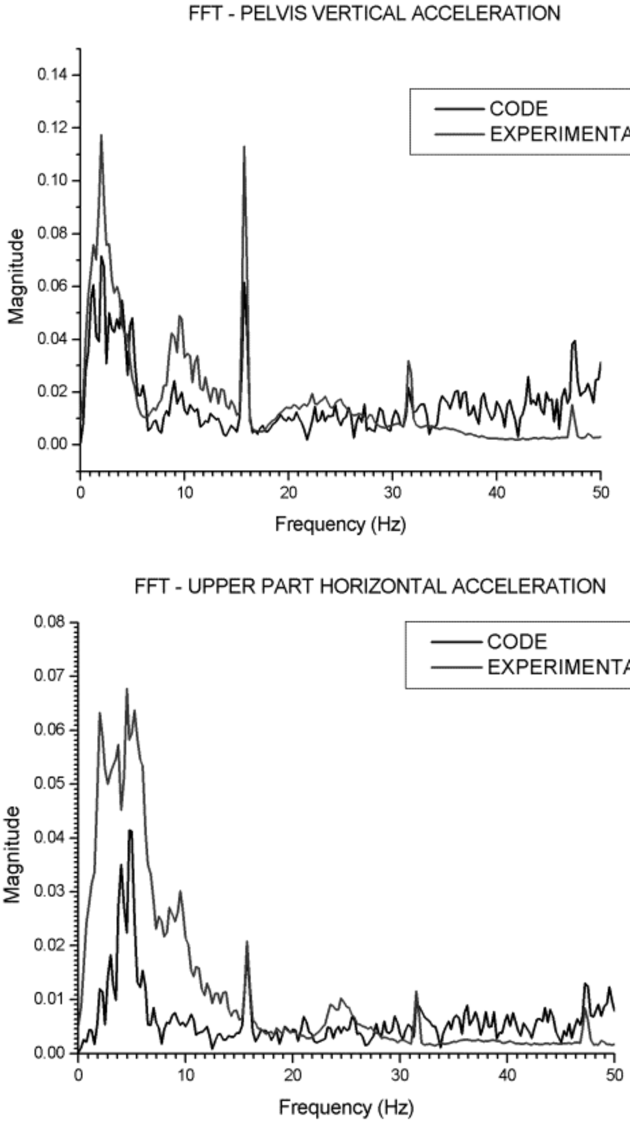
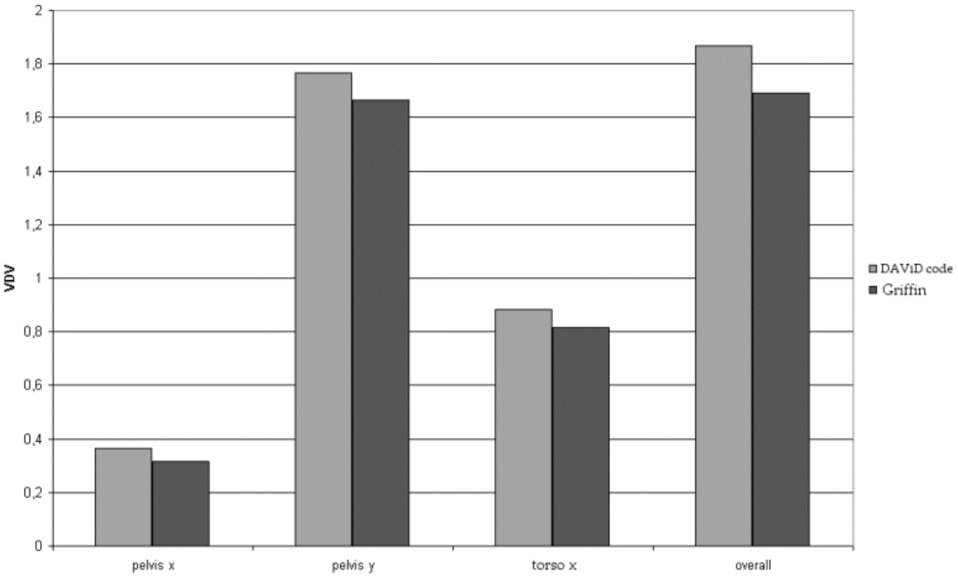


Figure 9 Experimental and numerical acceleration frequency response of pelvis and thorax



The acceleration signals have been processed according to the B.S. 6841 standard in order to compute VDVs. In Figure 10 an example of computed VDV is presented. The figure is about the comparison between Griffin's experimental data (Lewis and Griffin, 1998) and the numerical results coming from DAViD multibody model on a similar scenario of a car driven on an highway at 100 km/h. As it is clear, the overall VDV is mainly affected by signals along the vertical (*y*) direction. Other details about the influence of several posture parameters can be found in Pennestrì et al. (2005).

Figure 10 Comparison between comfort indices (VDVs)

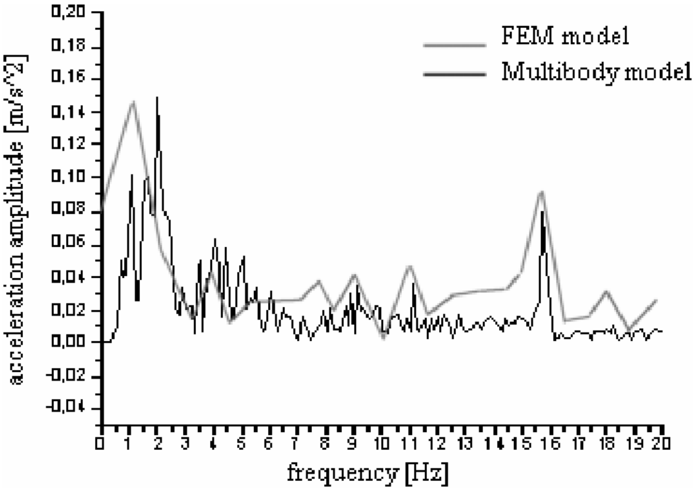


5 Discussion and conclusions

The simulated scenarios have underlined the differences between the two models. First of all, let us focus on the advantages and disadvantages of using the multibody model. This approach allows us to monitor the three dimensional behaviour of the virtual dummy, simulate different poses and model the human body properties requiring the definition of a small set of parameters. Moreover, the contact and the interaction with the surrounding car environment can be described using lumped spring-damper elements. For this reason, the computational time is reasonable (it takes about one hour on a personal computer to simulate ten seconds with 12 different inputs). This approach can easily handle simulations with different percentiles of occupants. However, the multibody model can not investigate the detail of the contact such as pressure distribution and the effect of different cushion shapes.

The finite element model is apt to investigate the contact and the interaction between the man and the seat but it requires many parameters to be defined, an accurate meshing algorithm and lengthy computations. For this reason the tested model has been built describing only one half of the dummy. The finite element model can also be used for vibrational comfort analysis. However, considering how it has been built, it can only simulate symmetrical inputs and the computational time may be unacceptable. The finite element model can include the analysis of local effects at joints and can produce information about the pressure distribution also in the inner part of the body. Hence, it is possible to detect high pressure values which may cause discomfort or health problems and correct posture or seat characteristics. The acceleration responses obtained from the two models are in good agreement (Figure 11).

Figure 11 Comparison between pelvis acceleration signals (vertical direction) of the proposed models



References

Amirouche, F.M.L., Xie, M. and Patwardhan, A. (1994) 'Optimization of the contact damping and stiffness coefficients to minimize human body vibration', *Journal of Biomechanical Engineering*, Vol. 116, pp.413–420.

Campanile, P., Celiberti, L., Barizzone, F., Rosati, A., Pennestrì, E. and Valentini, P.P. (2001) 'The development of a virtual dummy for the vibrational comfort analysis of car drivers', *Proc. on CD-ROM of 6th US National Congress on Computational Mechanics*, Dearborn, Michigan, USA.

Gonçalves, J.P.C. and Ambròsio, J.A.C. (2003) 'Optimal comfort response of road vehicle using flexible multibody dynamics', *Proc. on CD-ROM of ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Chicago, Illinois, USA.

Griffin, M.J. (1990) *Handbook of Human Vibration*, Academic Press, London, UK.

Gu, Y. (1988) *A Comparison Test of Transmissibility Response from Human Occupant and Anthropodynamic Dummy*, Society of Automotive Engineers, Inc, SAE Paper no. 980655.

Hairer, E. and Wanner, G. (1996) *Solving Ordinary Differential Equations II: Stiff and Differential-Algebraic Problems*, 2nd ed., Spring-Verlag, Berlin, Germany.

Haug, E.J. (1988) *Computer-Aided Kinematics and Dynamics of Mechanical Systems*, Allyn and Bacon, Boston, USA, Vol. 1, pp.48–104.

King, A.I. (1984) 'A review of biomechanical models', *Journal of Biomechanical Engineering*, Vol. 106, pp.97–104.

Kirchknopf, P. *et al.* (1995) *Development of a Multibody Calculation Model for the Passenger/Seat System Based on Experimental Results*, ATA paper No. 01A1085.

Kubo, M., Terauchi, F., Aoki, H., Isobe, M. and Okubo, K. (2000) 'Riding comfort affected by the properties of flexible polyurethane foams', *Proc on CD-ROM of 35th United Kingdom Group Meeting on Human Responses to Vibration*, ISRV, University of Southampton, England.

Lewis, C.H. and Griffin, M.J. (1998) 'A comparison of evaluations and assessment obtained using alternative standards for predicting the hazards of whole-body vibration and repeated shocks', *Journal of Sound and Vibration*, Vol. 215, pp.915–926.

Muskian, R. and Nash Jr., C.D. (1974) 'A model for the response of seated human to sinusoidal displacement of the seat', *Journal of Biomechanics*, Vol. 7, pp.209–215.

Pennestrì, E., Stefanelli, R., Valentini, P.P. and Vita, L. (2005) 'Using a virtual dummy to simulate vibration dose value for different car occupants', *Proceedings on CD-ROM of ASME-IDETC/CIE 2005*, Long Beach, California, USA.

Valentini, P.P. and Vita, L. (2002) 'DAViD: a multibody code to simulate a dynamic virtual dummy for vibrational comfort analysis of car occupants', *NATO-ASI on Virtual Nonlinear Multibody Systems Workshop Proceedings*, Prague, Cecz Rep., Vol. 1, pp.212–217.

Valentini, P.P. and Vita, L. (2003) 'DAViD: a multibody virtual dummy for vibrational comfort analysis of car occupants', *Virtual Nonlinear Multibody Systems*, NATO Science Series, Kluwer Academic Publishers, pp.253–262.

Vibration Injury Network (2001) *Review of Methods for Evaluating Human Exposure to Whole-body Vibration*, Appendix W4A to Final Report.

Wu, X., Rakheia, S. and Boileau, P.E. (1999) *Study of Human-Seat interactions for Dynamic Seating Comfort Analysis*, Society of Automotive Engineers, Inc., Paper no. 1999-01-1303, pp.135–146.

Zatsiorsky, V.M. (1998) *Kinematic of Human Motion*, Human Kinetics, New York, USA.