Some Observations Regarding the Nonlinearity Of Person/Seat Frequency Response Functions

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Abstract

This paper describes a short numerical investigation regarding the effect of human body nonlinearity on the frequency response function of vehicular person/seat systems. A nonlinear lumped parameter model of the seated human in the vertical direction was combined with a linear spring and damper representation of the seat cushion. Typical parameter values were taken and cross referenced against several previous studies. The equations of motion of the coupled system were time domain integrated under both random white noise excitation and under typical road excitation as measured from experimental tests in a European small car. Transmissibility functions calculated for the person/seat model were found to underestimate the nonlinear effects normally found in experimental data measured for automobile seats. The results suggest that either the nonlinear terms of the adopted human body model were underestimated in the previous study, or, more probably, that the seat cushion provides a much larger contribution to the overall nonlinear behaviour. The results suggest that further research should be directed towards modelling the dynamic behaviour of the seat cushion.

1. Introduction

Several automobile subsystems play a vital role in determining the overall Ride Comfort of a vehicle. These systems include the tyres, main suspensions, engine suspensions, car body and seat. Of these, the seat is particularly important as it comes into direct contact with the human occupant of the vehicle and is thus the final element of the vibration transmission chain. The dynamic behaviour of the person/seat system has been the subject of numerous studies, and test methods have been defined to quantify vibrational comfort [2,5].

A difficulty with assessing seat vibrational comfort is due to the nonlinear behaviour of various parts of the person/seat system. For the human body, nonlinear behaviour has several causes including the geometry of person/seat contact and the mechanical behaviour of human tissue [4]. For the seat, nonlinearities arise from the mechanical behaviour of materials such as the polyurethane foam which are dependent on factors such as temperature, humidity, preloading and time [2-3,8,11].

Because of nonlinearity, the vibrational response of the person/seat system depends on the choice of test signal. At least one previous study [2] has addressed this issue, and the results lead to a proliferation of test signals [2,5] with one reference vibration being associated with each of three principal driving conditions: motorway driving, city driving, and country driving. Time-variant analysis techniques have been applied in an effort to better understand the system response to the various road inputs [13], but current evaluation methods still rely on multiple test signals.

Since performing multiple experimental tests is time consuming and expensive, there is a need to develop synthetic models which summarise the system using only few parameters. Such an approach also has the advantage of providing simple models which can be used for performing numerical Ride Comfort simulations. Most studies performed to date have proposed linear lumped parameter models of one or more degrees of freedom for the person/seat system. A recent survey by Boileau et. all. [1] provides a summary of the various models and their frequency response characteristics. Nonlinear models are required, however, if the system behaviour needs to be known for a wide range or operating conditions. A recent study by Mansfield [10] has proposed nonlinear models for representing the apparent mass of the seated human body in the vertical direction.

This paper investigates the use of the Mansfield human body model as part of a coupled person/seat model. Experimental results from tests of an average European automobile seat are first shown to indicate the level of nonlinear effects which are normally observed in practice. A lumped parameter model is then described which consists of the nonlinear human body model plus a linear spring and damper unit for the seat cushion. Calculated transmissibility functions for the person/seat system are presented for several types and levels of acceleration input signal. Finally, the results are discussed and the importance of developing simple models of the seat cushion is emphasised.

2. Nonlinear Behaviour of the Combined Person/Seat System

Past research has established that the measured characteristics of a person/seat system vary as a function of the vibration level induced by the road [2,5-6]. Transfer functions, S.E.A.T. [6] indices and other objective measures are dependent on the input signal used. Further, it is generally accepted that the person/seat system presents a "softening" behaviour, one in which the main system resonance frequency is reduced as the excitation level increases.

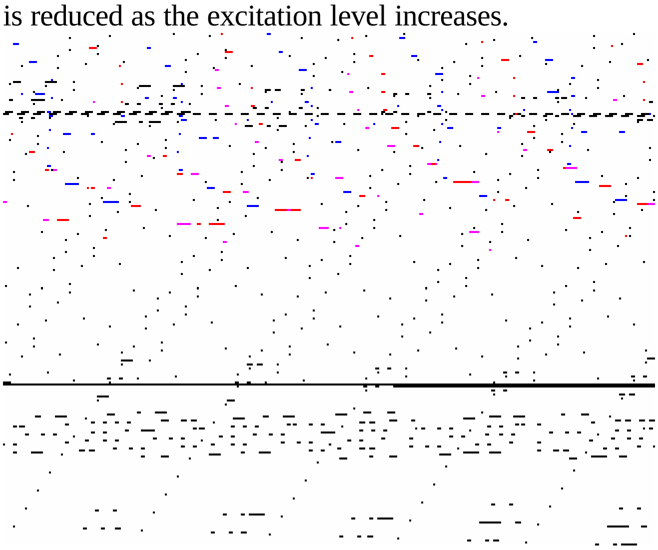

Figure 1) Experimentally measured transmissibility functions from the vehicle floor to the cushion in the vertical direction.

Figure 1 presents examples of typical person/seat transmissibility functions measured experimentally in the vertical direction from the vehicle floor to the surface of the seat cushion. The input vibrations used for the tests were measured in a small European automobile which was tested over road surfaces similar to those described in reference 5. The test surfaces were a motorway segment, a cobblestone surface (city road) and a segment of asphalt with large cracks and indentations of over a centimetre in depth (country road). The vertical direction RMS acceleration levels of the motorway, city road and the country road signals were 0.44 m/s^2, 1.75 m/s^2 and 1.82 m/s^2 respectively. As can be seen from Figure 1, the frequency of the main system resonance shifts to progressively lower values as the input level increases. Representing the "softening" dynamics is a necessary first requirement for a nonlinear system model.

3. Nonlinear Lumped Parameter Model of the Human Body

A recent study by Mansfield [10] proposed modelling the apparent mass of the seated human body in the vertical direction by means of nonlinear lumped parameter models. A single degree of freedom system model with four parameters as shown in Figure 2 was suggested. A base mass represents that part of the buttock and legs which does not move relative to the seat surface, a spring and damper describe the behaviour of the spine and the tissues of the back, and a large mass represents the upper body.

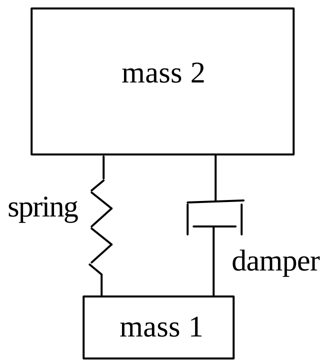

Figure 2) Lumped parameter model of the human body from reference 10.

Nonlinearity is incorporated into the model by adding nonlinear terms to the spring, damper and mass. The spring restoring force was expressed by

$$F_{spring} \quad = \quad k\,x \,+\, k_3\,x^3 \qquad (1)$$

while the damper was made nonlinear by adding a dry friction term to the viscous damper

$$F_{damper} \quad = \quad \pm\,(c|\dot{x}| + C) \qquad (2)$$

and the mass of the upper body was made nonlinear by making a part of the inertia force proportional to the displacement

$$F_{mass} \quad = \quad m\,\ddot{x} + |x|\,k\,M\,\ddot{x} \qquad (3)$$

where m is the linear component of the inertia force and the constants M and k describe the nonlinear component. The mass nonlinearity is of the type encountered when describing the dynamics of an inverted pendulum.

The parameter values [10] for the nonlinear model terms were determined by fitting the model response to median apparent mass data from 12 human subjects measured at 6 different magnitudes of white noise vibration in the frequency band from 0 to 20 Hz. The RMS amplitude levels of the experimental test signals ranged from 0.25 to 2.5 m/s^2.

4. Nonlinear Lumped Parameter Model of Person/Seat System

To evaluate the importance of human body nonlinearity towards the overall response of the person/seat system, a standard two degree of freedom lumped parameter model was defined in which the linear human body parameters were substituted by the nonlinear terms suggested by Mansfield. The model is shown below as Figure 3.

In the model k_1 is a linear term which represents the spring stiffness of the seat cushion and c_1 is a linear term which represents the cushion damping. The mass m_1 represents the mass of the body and legs that does not move relative to the seat surface. The nonlinear spring $k_{nonlinear}$ represents the stiffness of the upper body, the nonlinear damper $c_{nonlinear}$ represents the damping of the upper body and $m_{nonlinear}$ represents the nonlinear mass of the upper body which moves relative to the seat surface. The reaction forces produced by the nonlinear body elements are defined by equations 1, 2 and 3. The parameter values used are given in Table 1.

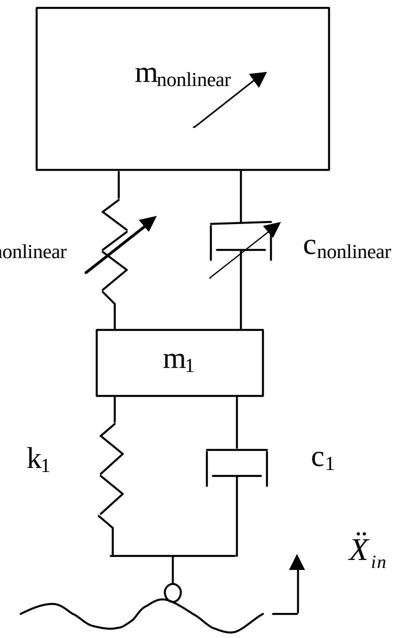

Figure 3) Nonlinear lumped parameter model of the person/seat system.

Parameter	Value
k_1	70,000 N/m
c_1	150 Ns/m
m_1	6 kg
k	38,533.3 N/m
k_3	-2.0E9 N/m
c	1360 Ns/m
C	2 N
m	45.6 kg
M	6.91 kg

k	1200

Table 1) Model Parameters

The linear parameter values for the seat cushion (k_1 and c_1) were taken from references 2 and 12 and can be considered average properties for European car seats. The human body model parameters were taken from reference 10 and represent a worst case scenario in which all the possible nonlinearities investigated in that study are taken in conjunction. One change to the Mansfield parameters was to take the mass m_1 to be 6 kg as in references 6 and 7.

5. Numerical Simulations

The person/seat model was implemented in Simulink◆ [14] and was evaluated by means of direct time domain integration. The integration scheme chosen was Runge Kutta 45 (RGK45). Input to the system was such that the floor acceleration signal ($\ddot{X}_{in}$) was a band-limited random white noise signal.

A first set of simulations was performed using random signals for the floor input. A 100,000 point random signal was produced using a sampling rate of 100 Hz. A 6th order bandpass Butterworth filter was next applied to the data so as to limit the energy to the frequency range from 0.4 to 25 Hz. Scaled copies of this signal were then produced so as to provide a family of input signals whose vibration levels spanned the range normally found when performing Ride Comfort studies of automobiles. The RMS acceleration amplitudes ranged from 0.01 to 1 g.

The system of equations was time domain integrated and the output accelerations of the two masses were obtained. Transmissibility functions were calculated from the floor to each of the two masses by means of the TFE command of Matlab◆ [15] using a 2048 point time data block, a Hanning Window and 70% overlap.

Figures 4 and 5 present the transmissibility functions from the floor to the lower body mass (m_1) and from the floor to the upper body mass ($m_{nonlinear}$) for the model of Figure 3. It can be seen that, under random white noise excitation, the nonlinear human body model terms did not cause large shifts in the system main resonance.

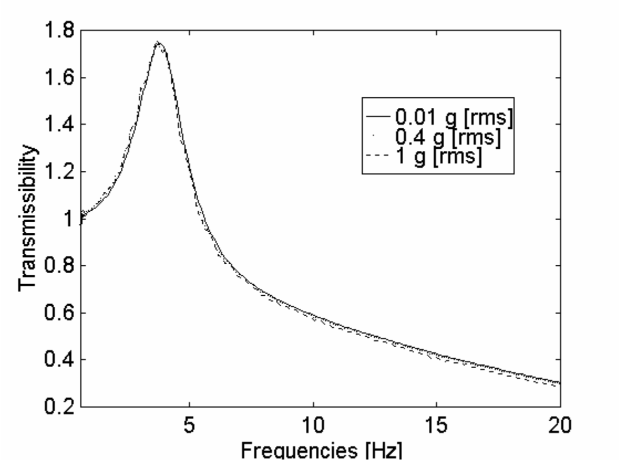

Figure 4) Transmissibility function from the floor to mass m_1 for various levels of random white noise acceleration input.

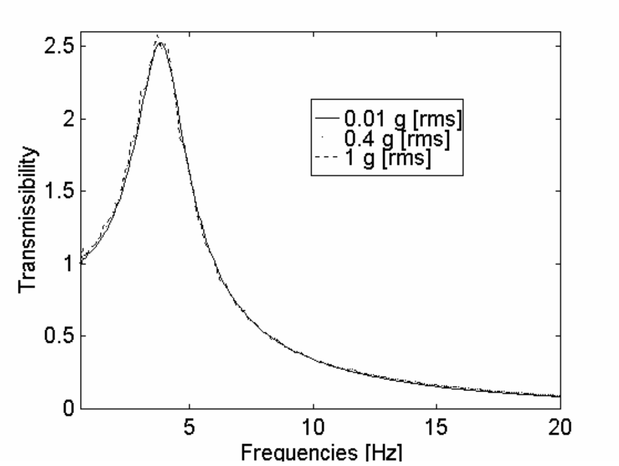

Figure 5) Transmissibility function from the floor to the upper mass $m_{nonlinear}$ for various levels of random white noise acceleration input.

Figures 6 and 7 present the transmissibility functions calculated using as the input signal the experimentally measured seat guide accelerations used to calculated the transmissibility functions of Figure 1. The acceleration data had a sampling rate of 256 Hz and was anti-aliasing filtered. As in the case of the random white noise excitation, the person/seat model demonstrated only weakly nonlinear behaviour when subjected to the experimentally measured road input.

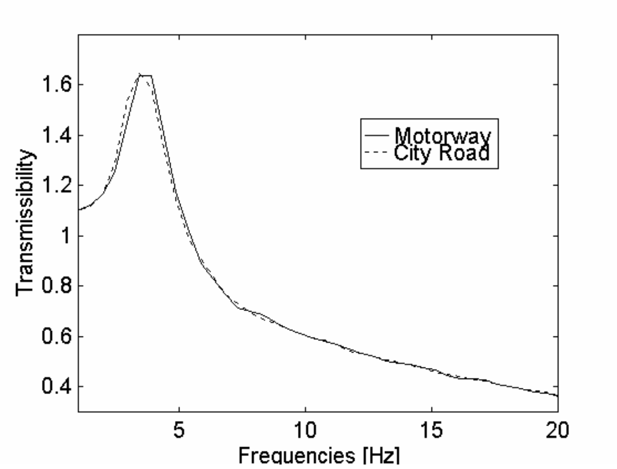

Figure 6) Transmissibility function from the floor to mass m_1 for the motorway and for the city road acceleration inputs.

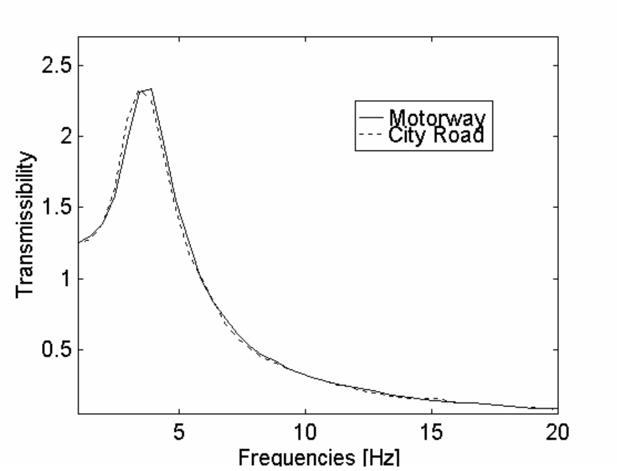

Figure 7) Transmissibility function from the floor to $m_{nonlinear}$ for the motorway and for the city road acceleration inputs.

To investigate the possible role of cushion nonlinearity in causing the frequency shifts typically found when testing real seats, the model of Figure 3 was modified to include a cubic stiffness term for the seat cushion. A cubic spring stiffness of –4E10 N/m was added to the linear spring k_1 of 70,000 N/m.

Figures 8 and 9 present the transmissibility functions calculated using the random white noise input signals. It can be seen that adding a cubic term to the seat cushion stiffness has moved the system main resonance. The frequency shift in this case was closer to the values normally found in experimental measurements.

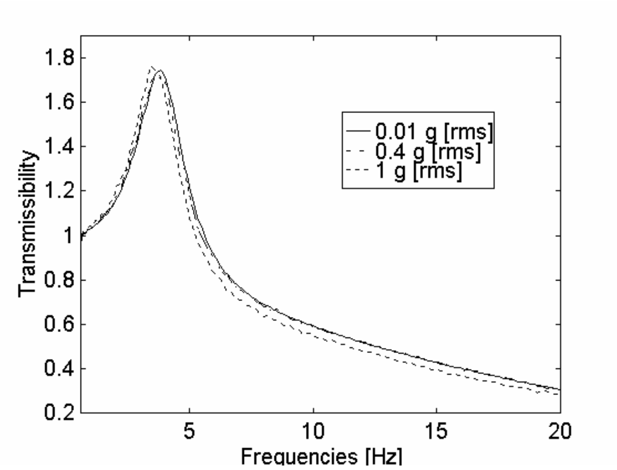

Figure 8) Transmissibility function from floor to mass m_1 for the seat cushion with added cubic stiffness term.

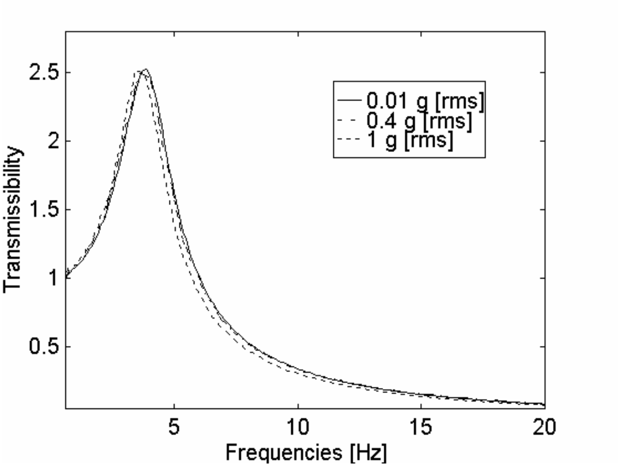

Figure 9) Transmissibility function from floor to upper mass $m_{nonlinear}$ for the seat cushion with added cubic stiffness term.

6. Discussion and Conclusions

A previous study by Mansfield [10] defined a set of nonlinear terms which provide a lumped parameter model of the human body in the vertical direction which exhibits properties of the same order of those that are measured experimentally. The model was found to provide a good fit to the experimentally measured apparent mass of 12 human subjects.

In this study, the nonlinear human body was coupled with a linear model of the seat cushion. The results from numerical simulations using both random white noise acceleration inputs and acceleration inputs measured in an automobile show that the nonlinear body model was not sufficient to represent the full "softening" behaviour normally encountered when experimentally testing car seats.

At least two possible explanations can be proposed. The first is that the nonlinear terms of the human body model are somewhat underestimated by the previous study, which may be the result of the test signals used. The experimental tests were performed using random white noise excitation of relatively low amplitude, the strongest test signal having an RMS acceleration of 2.5 m/s^2 (.25 g). Nonlinear model terms are often easier to accurately identify using high excitation levels, especially if performed with signals which provide a low crest factor.

A second and more probable explanation is that the largest nonlinear terms are actually those associated with the seat cushion materials or with the interaction which occurs between the seat and the occupant at the seat surface. Preliminary calculations such as those of figures 8 and 9 suggest the order of cubic term which must be added to the seat cushion spring to produce realistic behaviour of the overall transmissibility function for the complete system.

It can be concluded that the current state-of-the-art in person/seat lumped parameter modelling is not sufficient to model the system behaviour over the full range of excitation inputs normally encountered when performing Ride Comfort studies. Further research is necessary in order to select nonlinear model terms for the seat cushion which can be time domain integrated for simulation. Such cushion models could be systematically applied for both synthetically describing and modelling seats.

Acknowledgements

The authors would like to thank Mr. Luca Enrietti and Mr. Hans-Peter Mischer of Lear Seating Corporation for their help.

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