

## Theoretical and Experimental Ride Comfort Assessment of a Subject Seated into a Car

2010-01-0777

Published  
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### ABSTRACT

A comprehensive research is presented aiming at assessing the ride comfort of subjects seated into road or off-road vehicles. Although many papers and books have appeared in the literature, many issues on ride comfort are still to be understood, in particular, the paper investigates the mutual effects of the posture and the vibration caused mostly from road unevenness. The paper is divided into two parts. In the first part, a mathematical model of a seated subject is validated by means of actual measurements on human subjects riding on a car. Such measurements refer to the accelerations acting at the subject/seat interface (vertical acceleration at the seat cushion and horizontal acceleration at the seat back). A proper dummy is used to derive the seat stiffness and damping. An in-depth theoretical analysis is performed to assess how random vibrations may affect the validation of the mentioned mathematical model having five degrees of freedom (head, torso, legs and feet) and 30 parameters. In the second part of the paper a sensitivity analysis is performed based on the validated mathematical model. A number of different ride comfort indices (SEAT, K (VDI), VDV, ...) are accounted for. A number of different roads are considered. The parameters referring to the posture seem the ones influencing mostly the ride comfort, together with the seat cushion damping. Other parameters have less important effects.

### INTRODUCTION

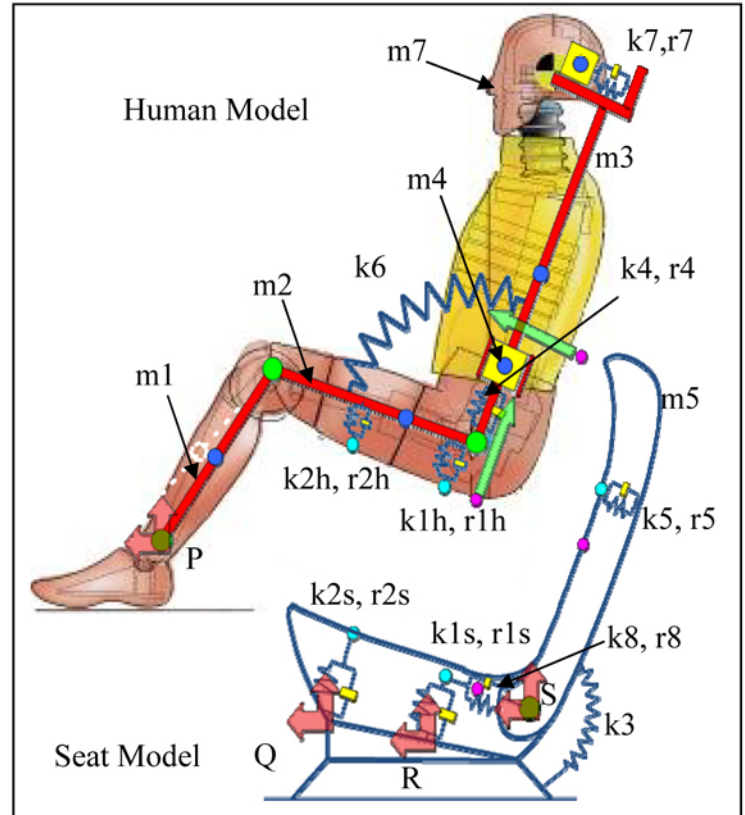
The ride comfort of road vehicle occupants is determined by a number of factors like the weight and the height of the subject but also by less obvious variables like the age, the posture, the gender, the position of the footrest, the presence and the angle of the backrest [2,17]. All these sources of variation lead to a large number of time consuming experimental measurements to assess ride comfort. The

exposure to whole body vibration (WBV) has negative effects on many activities -especially driving- that becomes difficult or even precluded over certain vibration level [2,7,8,9,10,11,13]. In the long term WBV can lead to permanent back ache or spine troubles [13]. The most significant standards for comfort evaluation are VDI 2057 [12], ISO 2631 [3,4,5,6] and UNI ENV 12299 [11]. Standards define a discomfort indicator depending on accelerations measured on the principal human - vehicle interface, weighted by means of experimental human perception curves, actually the manner in which vibration affects health, comfort and motion sickness is dependent on the vibration frequency content. Many models reproducing the seated human transmissibility exists [2,16,17,18,19,20,21] and different mathematical models able to reproduce the human response to vibration have been developed [33,34,35]. Virtual models of the human body, mainly based on the finite element modeling technique, have been developed to get the contact pressure pattern between the human body and the seat cushion [38,41]. However, just a few simple dummies for vehicle vibration transmissibility evaluation have been realized [31,32,37]. All of the models proposed in literature do not consider, at the same time, the vertical and the longitudinal vibrations.

In this study, starting from a number of experimental measures, a model of the seated human subject has been derived and validated. The model reproduces the accelerations measured on the contact surfaces between different human subjects and different vehicle seats. The construction and the validation of a mechanical dummy (MaRCo), corresponding to the mathematical model derived previously was performed. Both the model and the dummy can be useful for optimal seat design or existing seats evaluation.

The paper is organized as follows. In Section 1 the mathematical model representing the combination of a seated person and of an automotive seat is presented. Section 2 deals with the experimental validation of the model. The construction and validation of dummy is presented in Section 3, while Section 4 introduces the most important indices for comfort evaluation, according to the main international standards. In Section 5 a sensitivity analysis of these indices is carried out, referring to the mathematical model discussed in Section 1.

The mechanical model studied in this paper is called “full model” (Fig. 1) and it is composed by a sub-model which represents the seat (seat model) and by a second sub-model that reproduces the human subject behavior (human model).



### 1.1. HUMAN MODEL

The human model has a human-like structure ([Fig.1](#)), 5 d.o.f. and it is described by means of 32 parameters (5 masses, 5 stiffness elements, 4 damping elements, 15 linear dimensions, and 3 angular dimensions), for a detailed explanation of all the parameters see [Appendix A](#). The human model is composed by three links representing respectively the lower legs, the thighs and the torso. An additional mass is added to reproduces the head, and another one is positioned in a way that the human abdomen moving mass can be simulated. All of these elements are linked each other by means of plane hinges and elastic-damping elements for simulating the effect of the human anatomical joints and muscles. The motion of the system is assumed to be planar (in the longitudinal-vertical plane). The five d.o.f. of the human model are:

- $\alpha_1$  lower leg rotation (with respect to car body)
- $\alpha_2$  thigh rotation (with respect to lower legs)
- $\alpha_3$  torso rotation (with respect to thighs)
- $x_4$  internal mass displacement (with respect to torso)
- $x_7$  head displacement (with respect to torso)

Twelve parameters of the human model have to be identified (once the seat parameters are measured) as they strongly depend on the human subject under consideration. They are listed in [Appendix A Tab. A1](#). The other model parameter values can be determined rather easily [2,25]. These parameters are listed in [Appendix A in Tab. A2](#).

The full model is excited by the acceleration, the velocity and the displacement of the points P, Q, R, S shown in [Fig. 1](#). The full model outputs are:

- the acceleration  $A_{zz}$  measured at the seat cushion-human body interface orthogonal to the seat cushion
- the acceleration  $A_{xx}$  measured at the seat backrest-human body interface orthogonal to the seat backrest

The detailed scheme of the full model is reported in [Appendix A, Fig. A.1](#).

## 1.2. SEAT MODEL

The seat model is shown in [Fig.2](#) and it is described by means of ten parameters

<[figure 2](#) here>

The seat model includes an additional d.o.f. and 10 parameters (1 mass, 5 stiffnesses, 4 dampings). The additional d.o.f. represents the movement of the seat backrest. To measure the values of the seat parameters an anthropometric dummy, named MaRCo (based on SAE J826), has been used. The local stiffness of the cushion depends on the actual deformed shape of the cushion itself so, during the measure of  $k_{1s}$  and  $k_{2s}$ , a special bottom shell for the dummy has been adopted. This shell is conceived in such a way that it has the same shape of the interface between the cushion and a 50th percentile-man human subject. Actually such a shell has been formed when a subject was seating on the seat. For the measurement of  $k_{1s}$  and  $k_{2s}$  values the dummy has been seated on the seat under test and slightly different loads have been applied to the dummy. The corresponding slight displacements at the  $k_{1s}$  and  $k_{2s}$  location have been measured by means of four 1/100 mm dial indicators ([Fig. 3](#)). The resulting figures represent the combination of both the cushion and the seat structure stiffnesses.

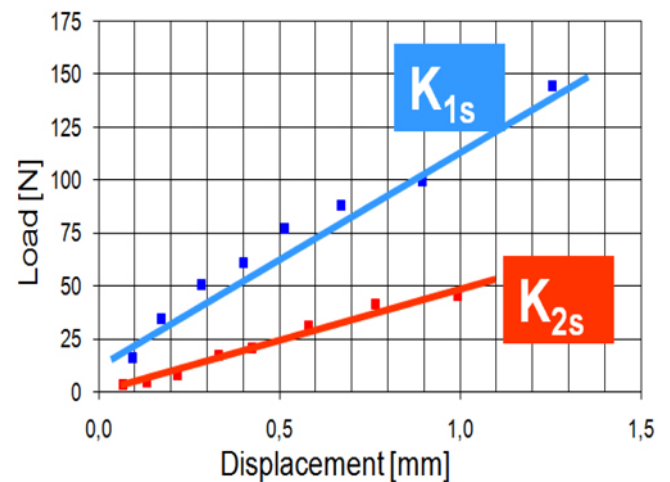
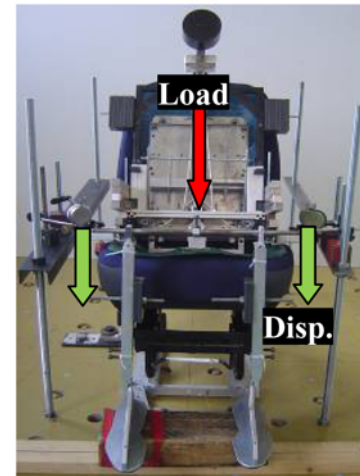


**Fig. 3.  $k_{1s}$  and  $k_{2s}$  measurement.**

The same approach has been adopted for the measurement of  $k_3$ ,  $k_5$  and  $k_8$ : a known load has been applied (by means of a load cell or calibrated masses) and the resulting displacements have been measured ([Fig. 4, 5](#)).

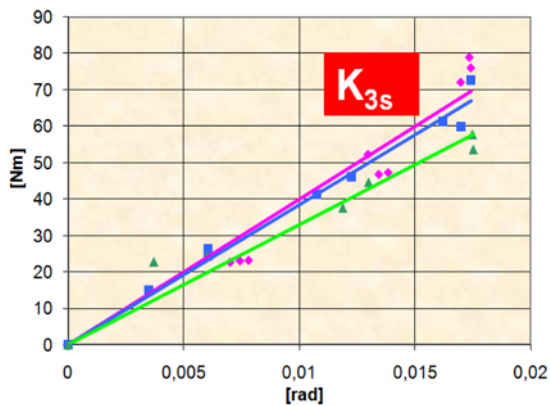
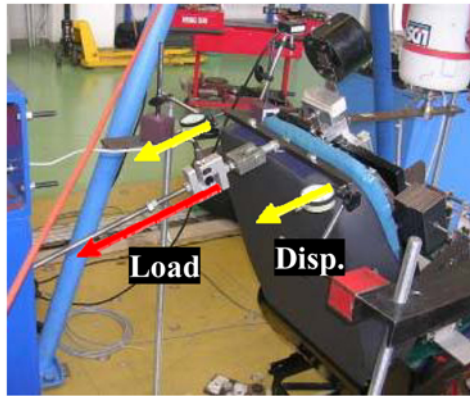


*Fig. 4. k3 measurement.*

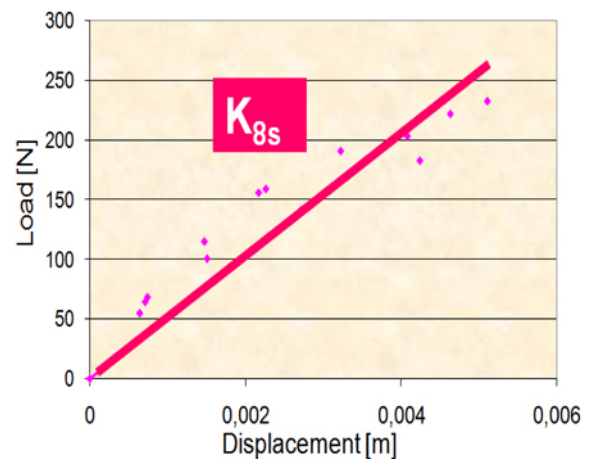
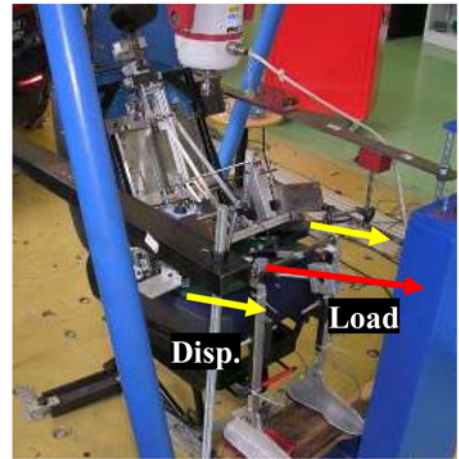


*Fig. 5. k8 measurement.*

The measurement of the damping characteristics of the seats has been performed by means of an electric shaker equipped with a load cell and a laser displacement sensor. Two round plates of different sizes have been fitted on the shaker end. The shaker can move at different frequencies and strokes. The measure has been performed spanning from the frequency of 1 Hz up to 20 Hz with a frequency interval of 0.5 Hz. The shaker has been positioned at different locations with its end equipped with the round plate perpendicular to the cushion and to the backrest (Fig. 6). From the measured force and displacement the cushion and backrest damping has been identified. A 1 d.o.f. model gives satisfactory agreement between the measured and calculated accelerations (Fig. 7).



*Fig. 6. Seat damping measurement.*

<figure 7 here>

## 2. VALIDATION

The validation of the model is based on acceleration measurements on different subjects seated into a vehicle running on uneven road and on the measurement of the stiffness and damping characteristics of different vehicle seats. During the tests, the vertical (cushion) and the longitudinal (backrest) accelerations between the seat and the seated human subject have been measured in addition to the accelerations on the vehicle body. Two accelerometers were positioned on the seat by means of two rubber pads. One accelerometer was positioned on the seat cushion, in the median seat longitudinal plane at the intersection between a vertical line passing through the midpoint of the segment joining the two H-points (see Fig. 1), and the cushion itself; the accelerometer axis was oriented nearly perpendicular to the seat cushion. The second accelerometer was positioned on the seat backrest, again in the median seat longitudinal plane at 270 mm above the cushion level; the accelerometer axis was oriented against the subject's shoulders, close to perpendicular to the backrest.

The relevance of the accelerometer positioning has been investigated by means of the model parameters 'b' and 'd' (see §5). The actual position of the sensors has been

measured as precisely as possible before each test, obviously the accelerometer positions may slightly change during seat loading.

The test vehicle (a light commercial truck with basic design seats) was equipped with an inertial measurement unit (measuring three accelerations plus three angular velocities around three orthogonal axes) positioned near the vehicle centre of gravity to sense the vehicle body motion.

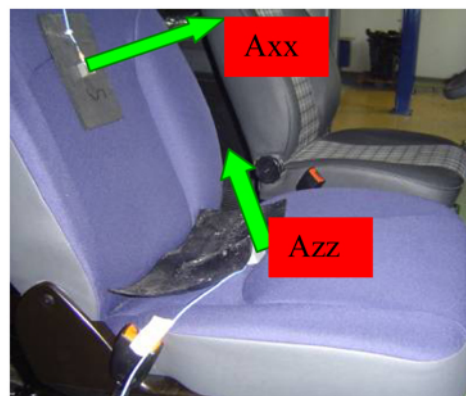


*Fig. 8. Instrumented test vehicle and accelerometers position.*

Before the data acquisition all the main anthropometric characteristics (weight, height, legs length, ...) of the subject were collected. Subjects have been chosen in order to maximize anthropometric diversity (ranging from tall and thin subjects to short and sturdy persons). Once the subject is positioned on the test vehicle its posture (lower legs, thigh and torso orientation and H point height) is measured and the test starts: the instrumented vehicle is driven along the test track trying to maintain speed as constant as possible. Each test track has been traversed at different velocities and tests have been repeated several times with the same subject in order to investigate inter-subject variability. In Fig. 9 an example of intra-subject variability of the vertical response and the variations in the dynamic response due to the modification of the muscle tension are shown.

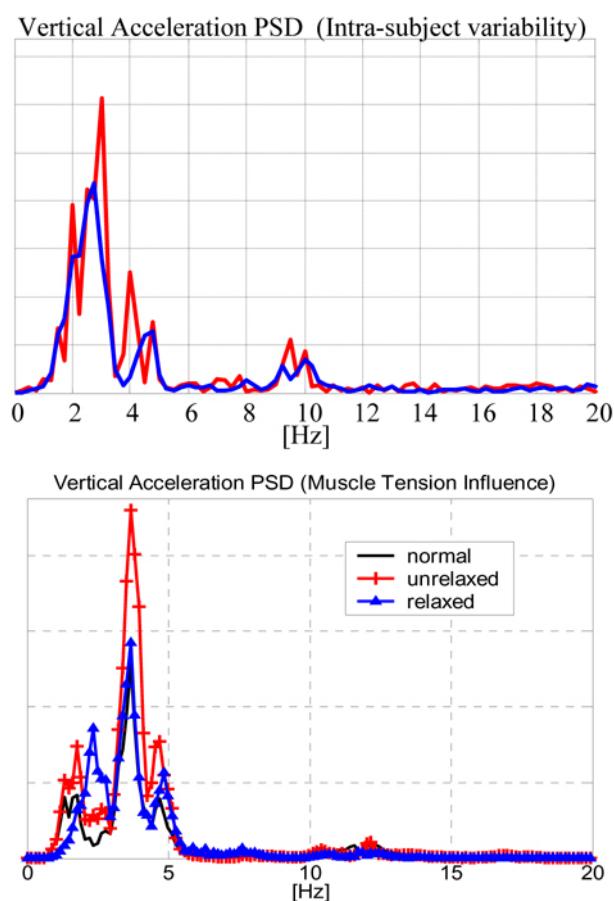


**Fig. 9. Intra subject variability and muscle tension influence**

Data have been recorded by means of a National Instruments 12 bit acquisition card DAQCard 700 and stored on a laptop. Acquisition frequency was 512 Hz.

Many test tracks have been traversed in order to have different kinds of excitation at the seat rails. They are either uneven road or roads with concentrated obstacles.

Due to the large number of parameters to be identified and to the complexity of the response surfaces, the identification process has been performed in two steps, at first, a quasi-Montecarlo minimization method has been used, followed by a further optimization (minimization of the errors) based on the gradient method. Referring to the quasi-Montecarlo minimization procedure, the 12 human model parameters to be identified have been varied within predefined ranges. The parameter values within the given ranges were defined according to a Sobol low discrepancy sequence of two thousand samples. A cost function between experimental data and calculated ones has been constructed to rank the parameters value combinations. The best performing parameters value combinations were used as the starting points for a further error minimization (optimization). Different cost functions have been considered:

- the mean square error between Power Spectral Density (PSD) of the measured and computed vertical acceleration at the seat cushion-body interface. The two PSD have been weighted, according to the weighting functions reported in [3] (to consider that the human perception of vibration is dependent on the vibration frequency content), and then normalized with respect the maximum value of the measured vertical acceleration PSD.
- the mean square error between Power Spectral Density (PSD) of the measured and computed longitudinal acceleration at the seat backrest-body interface. The two PSD have been weighted, according to the weighting functions reported in [3], and then normalized with respect the maximum value of the measured longitudinal acceleration PSD.

The definition of the cost functions is focused on the PSD signal since the definition of the discomfort index is based on the PSD of the acceleration [12].

The ranges in which the parameters to be identified can change, have been chosen in different ways. For the anthropometric parameters the range limits were determined on the basis of anthropometric tables in the literature (allowing to include both the 5th percentile European woman and the 99th percentile European man [25]).

In the following figures the results of the identification are shown. Figure 10 shows the comparison between the measured vertical acceleration (blue line) and the calculated one (red line) for the seat number 1 (left) and seat number 2 (right). The experimental data refer to the same subject so the human model parameters do not change in figure 10, while the seat parameters values are the measured ones, respectively for seat n° 1 and n° 2.