A study of biomechanical model of seated human body exposed to vertical vibrations

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Abstract. This paper presents a human biomechanical model with 4 degrees of freedom of a human body in a car seat with backrest exposed to vertical vibrations. The proposed model has been analysed for five various values of radian frequency as numerical input data, and the results were compared with the results obtained for similar models in the published literature. In the biodynamic analyses the model was simplified to linear system to reduce the complexity of analytical and numerical simulations.

1. Introduction

The human body is a complex biomechanical system, studied from the point of view of the analysis of human movements, especially of the normal and pathological human walking analysis [1-3]. Theoretical studies are supplemented with numerical simulations and virtual analyzes of the movement on virtual humanoid mannequins. The results are usually validated by experimental evaluations of the human joints movements in one plane (sagittal plane) or in two planes (sagittal plane and frontal plane), by using specialized acquisition and processing data systems. The experimental measurements used in the study of the human complex biomechanical system are based on data acquisition and processing systems dedicated to human biomechanical evaluations, as Biometrics system based on wearable sensors [1, 3-7], or systems based on video-cameras [2, 8]. The results of the studies are often used in the analysis of the stability of the human movement through the tools of nonlinear dynamic analysis [6, 7, 9,10], or for the purpose of designing and analyzing of bio-inspired robotic structures, such as exoskeletons and orthotic systems used in the rehabilitation of human movements [4-17] or robotic structures used in minimally invasive surgery [18-20].

The studies of the importance of vibration analysis and their effects on the human body represents a large domain in the specialized literature, therefore many studies have focused on the biodynamic response of the human body subjected usually to vertical vibrations. Several studies are focused on analyzing the biodynamic responses of a driver exposed to vibrations but also on the research regarding the transmissibility of vibrations of the whole body in different postural conditions. The study of the action of mechanical vibrations on the human body considers the analysis regarding the risk of deteriorating the health status of the human body due to the exposure to global vibrations with high intensity of the human body.

Previous studies regarding the analysis of the biodynamic responses of the human body exposed to vertical vibrations, as well as the transmissibility of the vibrations taking into account body position during driving, head position, type of seat, the speed of the vehicle, the masses of the segments of the human body, as well as the type or category of the road are published [21-29].
A study in which a biomechanical model of the human body was developed in a sitting position on a backless seat is presented assessing the transmissibility of vibrations and the dynamic response of the human body subjected to vertical vibrations [26].

The biodynamic responses of the driver sitting on the seat were studied to define the frequency and intensity of vibrations in establishing the maximum limit of exposure of the human body, the human sensitivity, as well as the effect of vibrations felt by the driver during the ride to diminish the causes felt throughout the body due to vibration exposure [27].

Many scientific researches have been carried out in the construction of a specific biomechanical model for the measurement and appreciation of the response characteristics of a body placed to transmitted vertical vibrations. Thus, these responses were evaluated regarding the transmission of vibrations in the body, from the point of entry, respectively the seat, to the head (STH) [28-30].

In order to analyze the responses of a seated body exposed to vertical vibrations in the article [31], the experimental tests validating the mathematical models of a human body seated on a chair subjected to vertical vibrations were studied. The most representative mathematical models are those developed by Kim et al. [30], respectively the mathematical model developed by Cho and Yoon [31], both models being described for the representation of the driver in the sitting position with and without a backrest, exposed to vertical vibrations in different driving positions [32]. In order to determine the values of vibrations transmitted to the whole body, inertial sensors such as accelerometers or tri-accelerometers with head restraint are used to measure the vibrations transmitted to the head [33-35]. In [36] the vibrations of the whole body are measured using a tri-axial force plate (Kistler 9281C) and three force sensors on three axes, as well as a micro-accelerometer for measuring the vibrations transmitted to the head [37], [38]. The study and influence of vibrations on the human body can be found in articles [21-26], [35], [39-46]. In [35-36] the conditions of placement were studied, namely, the contact with the seat backrest, the angle of the backrest inclination and the position of the legs, reaching the conclusion that the optimal option is the one in which the driver is in the sitting position on a seat with a vertical backrest inclined to 110°. In [26] the influence of the speed on the vibrations to which the driver is subjected was studied, the conclusion being that a high speed leads to an increase of the intensity of vibrations.

The purpose of the article is to analyze the biodynamic responses of the human body subjected to vertical vibrations produced by an sinusoidal excitation for different values of radian frequency.

2. The biomechanical model of the driver

Figure 1 shows the biomechanical model of the driver in the sitting position while driving. We consider that the human body consists of 4 large segments, namely the head, having the center of gravity G1, the trunk with the center of weight G2, the basin represented by G3 and the legs having the center of weight G4. Ji notations represent the connection points between the parts of the human body. Each segment of the human body is attached to the systems consisting of springs and dampers and are marked with Ci and ki attached to each segment separately.

The figure shows the system of vertical and horizontal springs and dampers under G3 and G4 to characterize the deformable properties of the pelvis and the legs, but also the vibrations transmitted from the seat to the whole body. The other springs and shock absorbers for each segment are equivalent springs and springs, k eq and C eq. The proposed model is composed of 4 rigid segments with a total weight of 94 kg.
Figure 1. The biomechanical model of the driver

Figure 2 shows the equivalent system for the biomechanical model, with 4 degrees of freedom needed to solve the system of equations, where the seat mass is negligible and the force of the springs and dampers is solved by the Laplace method.

In the figure 2 are represented the masses of the segments of the human body that define our human biomechanical model. We noted $m_1$ - represents the mass of the head, $m_2$ - represents the mass of the trunk, $m_3$ - the mass of the basin and $m_4$ the mass of the legs, $k_i$ and $C_i$ represent the springs and dampers for each segment, $x_i$ represents the vertical displacement of each segment, $m_i$. 

Figure 2. The equivalent system attached to the biomechanical model of the driver
Table 1 Coefficient values and masses of the segments of the human body [38-40]

|                           | Segment 1 | Segment2 | Segment 3 | Segment 4 |
|---------------------------|-----------|----------|-----------|-----------|
|                           | Head      | Trunk    | Pelvis    | Legs      |
| Mass [kg]                 | m₁= 6.48  | m₂= 50.88| m₃= 11.36 | m₄= 25.76 |
| Spring constant [N/m]     | k₁ = 166.990 | k₂ = 10370 | k₃ = 20000 | k₄ = 144.000 |
| Damping Coefficient [Ns/m]| c₁ = 310  | c₂ = 163.9 | c₃ = 330  | c₄ = 2475  |

The masses of the segments of the human body are calculated taking into account the specifications in the specialized literature [39], and the values of the depreciation and elasticity coefficients are described in the article studied from the references [40].

The differential equations system attached to the biomechanical model of the driver:

\[
m_1 \cdot \frac{d^2}{dt^2} x_1(t) + c_1 \left( \frac{dx_1(t)}{dt} - \frac{dx_2(t)}{dt} \right) + k_1 \left( x_1(t) - x_2(t) \right) = 0
\]

\[
m_2 \cdot \frac{d^2}{dt^2} x_2(t) - c_1 \left( \frac{dx_1(t)}{dt} - \frac{dx_2(t)}{dt} \right) - k_1 \left( x_1(t) - x_2(t) \right) + c_2 \left( \frac{dx_2(t)}{dt} - \frac{dx_3(t)}{dt} \right) + k_2 \left( x_2(t) - x_3(t) \right) = 0
\]

\[
m_3 \cdot \frac{d^2}{dt^2} x_3(t) - c_2 \left( \frac{dx_2(t)}{dt} - \frac{dx_3(t)}{dt} \right) - k_2 \left( x_2(t) - x_3(t) \right) + c_3 \left( \frac{dx_3(t)}{dt} - \frac{dx_4(t)}{dt} \right) + k_3 \left( x_3(t) - x_4(t) \right) + c_5 \left( \frac{dx_3(t)}{dt} - \frac{dx_0(t)}{dt} \right) + k_5 \left( x_3(t) - x_0(t) \right) = 0
\]

\[
m_4 \cdot \frac{d^2}{dt^2} x_4(t) - c_3 \left( \frac{dx_3(t)}{dt} - \frac{dx_4(t)}{dt} \right) - k_3 \left( x_3(t) - x_4(t) \right) + c_4 \left( \frac{dx_4(t)}{dt} - \frac{dx_0(t)}{dt} \right) + k_4 \left( x_4(t) - x_0(t) \right) = 0
\]

3. Results

The system of equations related to the biomechanical model of a driver with a weight of 94 Kg, in the sitting position, exposed to vertical vibrations, was solved in Maple Software18 with the method symbolically solved, transformed Laplace. In this work, the sinusoidal road profiles excitation is adopted to evaluate the proposed system. The sinusoidal excitation equations are listed below:

\[x_0 = A \sin(\omega \cdot t)\]

where, \(\omega\) is the radian frequency.

This study assumed that the \(A=0.035\) m.

The characteristic curves for each unknown in the system of differential equations, namely \(x_1, x_2, x_3\) and \(x_4\), are obtained. For the present study, the initial conditions are considered:

\[x_1(0) = 0 \quad x_2(0) = 0 \quad x_3(0) = 0 \quad x_4(0) = 0 \]
\[x_1'(0) = 0 \quad x_2'(0) = 0 \quad x_3'(0) = 0 \quad x_4'(0) = 0 \]

The results presented as curves in Figures 3-7 shows the displacement histories obtained for the amplitudes of vibrations \(x_1\)-head considering different values for \(\omega\): 1 rad/s, 2 rad/s, 3 rad/s, 5 rad/s and 10 rad/s. For torso, pelvis and thigh (\(x_2, x_3\) and \(x_4\)) the diagrams are similar, and they are no more presented.
Case 1: $\omega=1$ rad/s

![Image](image1)

**Figure 3.** The vibration variation function of time, in the vertical direction, $x_1$

Case 2: $\omega=2$ rad/s

![Image](image2)

**Figure 4.** The vibration variation function of time, in the vertical direction, $x_1$

Case 3: $\omega=3$ rad/s

![Image](image3)

**Figure 5.** The vibration variation function of time, in the vertical direction, $x_1$
**Case 4: \( \omega = 5 \text{ rad/s} \)**

![Figure 6](image)

**Figure 6.** The vibration variation function of time, in the vertical direction, \( x_1 \)

**Case 5: \( \omega = 10 \text{ rad/s} \)**

![Figure 7](image)

**Figure 7.** The vibration amplitude, function of time, in the vertical direction, \( x_2 \)

4. **Discussions**

The proposed model with 4 degrees of freedom is considered as a good structure to describe the process of transmissibility of vertical vibrations throughout the body, more precisely, the 4 large body segments modeled and represented in figure 1. Through the systems formed by springs and associated dampers, each segment of the human body, denotes a vertical movement of vibrations transmitted from the chair to the head. In the described biomechanical model, the segments of the human body \( G_1, G_2, G_3 \) and \( G_4 \) are connected by means of springs and dampers, moving only in a vertical direction. This model does not describe the rotation movement of the head very well, namely, \( G_1 \).

The biomechanical model of the driver is limited to the seating position with the feet sitting on the floor, with backrest, with seat mass negligible. The system generates the characteristic curves for the excitation amplitudes of the vertical displacements of the four segments masses.

Thus, the characteristic curves of the variation of the vibrations \( x_i \) in the vertical direction, as a function of time, are represented graphically by using Maple Software; each characteristic \( x_i \) generates a characteristic curve to the graph for the initial conditions imposed on the system and different values for \( \omega \).
The values obtained and the graphs describing the characteristic curves of the vertical vibrations of the segments’ masses of our biomechanical model are comparable with those obtained in other published papers [40].

5. Conclusions
In the present paper, a study of a 4-DOF biomechanical model of a seated human body exposed to vertical vibrations has been implemented. The model proposed in this research has been analysed for five various values of radian frequency, as numerical input data, and the results compared with the results obtained for similar models in the published literature. In the biodynamic analyses the model was simplified to linear system to reduce the complexity of analytical and numerical simulations.

Future research will be extended to the following.
(1) Taking into account that the mass of a seated body influences on certain biodynamic response functions, further research will consider the influences of different mass values.
(2) Development of a more complex biomechanical model, with an increased number of degrees of freedom and experimental tests based on wearable sensors, as accelerometers type and a dedicated software to acquire and process the vibrations, NexGen, will be performed.
(3) Experimental tests will be performed in various driving postures and for different types of roads, in order to validate the corresponding mathematical model.

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