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VIBRATION TRANSMISSIBILITY BEHAVIOUR OF SIMPLE BIODYNAMIC MODELS USED IN VEHICLE SEAT DESIGN

PRZENOSZENIE DRGAŃ W PROSTYCH MODELACH BIODYNAMICZNYCH UŻYWANYCH W PROJEKTOWANIU FOTELI DLA POJAZDÓW

A b s t r a c t

Five biodynamic models are investigated to approximate vertical seat vibration transmissibility and mechanical impedance in an effort to reduce experimental time and data collection when designing vehicle seats. The research has found that these biodynamic models of two, three and four degrees of freedom are ideally suited for initial seat design, since whole body vibrations can be easily depicted at approximately 5Hz. Further research is necessary to investigate the resonant frequencies for defined anatomical structures, passenger variability and the use of a backrest support.

Keywords: biodynamic model, vehicle seat, vibration transmissibility, mechanical impedance

S t r e s z c z e n i e

W artykule przedstawiono porównanie przenoszenia drgań oraz impedancji mechanicznej dla pięciu prostych modeli biodynamicznych używanych w procesie projektowania foteli dla pojazdów. Przedstawione modele są używane w obliczeniach w celu ograniczenia czasu badań eksperymentalnych i zbierania danych podczas procesu projektowania produktu. Badania wykazały, że porównywane modele o dwóch, trzech i czterech stopniach swobody dają bardzo dobre wyniki na wstępnym etapie projektowania siedzeń. Analiza wykazała, że dalsze prace są potrzebne do zbadania częstotliwości rezonansowych dla określonych cech budowy anatomicznej oraz różnych cech osobniczych dla populacji pasażerów.

Słowa kluczowe: modele biodynamiczne, siedzenia pojazdów, przenoszenie drgań, impedancja mechaniczna

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1. Introduction

The human body is exposed to various whole body vibration inputs from vehicles on a daily basis. These vibrations cause: increased driver fatigue; poor concentration during driving, pain and discomfort experienced in the lower back and neck regions, depending upon the exposure duration and magnitude [6, 11, 2, 7]. It is therefore critical that whole body vibration are limited or eliminated on vehicle seats.

The development of an idealized seat has prompted many researchers to measure vertical vibration transmissibility for the seated human; however, such measurements are inefficient and expensive, and do not adequately represent the physiological and psychological reactions of a person [7]. The utilization of biodynamic models to perform simulations during the seat design process is thus a useful and inexpensive tool that can be used in different vibration environments without the need of costly experiments or using commercially available software.

2. Biodynamic Models and Vibration Transmissibility Behavior

Five biodynamic models with equations of motion given in equations (1) to (11) are proposed to simulate vibration seat transmissibility with mechanical impedance associated with major body resonances, and compared to experimental data and published standards. The aim of this paper is to compare different biodynamic models subjected to vertical seat vibration, which are confined between two to four degrees of freedom (DOF) in order to find a simple and reliable model that can adequately simulate the vertical vibration transmissibility and mechanical impedance properties of a human for the purpose of initial seat design.

2.1. 2-DOF Model by Griffin (1990)

Fig. 1 below consists of 3 masses where m_1 lacks anatomical description and m_2 represents the feet, supported by a footrest.

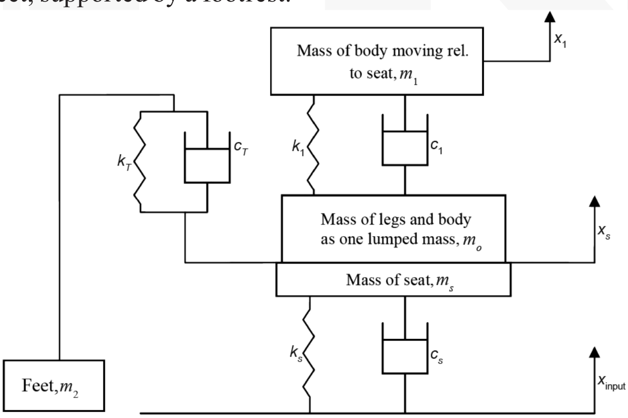

Fig. 1. Schematic of 2 DOF model by Griffin

The thigh stiffness and damping k_T and c_T as well as mass m_2 are neglected since the footrest moves in phase with the seat [4] whereas the legs and thighs are considered as one lumped mass m_o, which does not move relative to the seat. Equations of motion for this model are shown below – (1) and (2).

$$m_1 x_1 = k_1 \left(x_s - x_1\right) + c_1 \left(\dot{x}_s - \dot{x}_1\right) \tag{1}$$

$$\left(m_o + m_s\right)\ddot{x}_s = k_1 \left(x_1 - x_s\right) + k_s \left(x_{input} - x_s\right) + c_1 \left(\dot{x}_1 - \dot{x}_s\right) + c_s \left(\dot{x}_{input} - \dot{x}_s\right) \tag{2}$$

The 2 DOF model is designed to simulate the driving point mechanical impedance and behavior of vibration transmissibility response from the seat person interface to the rest of the human body.

2.2. 2-DOF Model by Rakheja, Afework, and Sankar (1994)

The model shown in Fig. 2 characterizes the dynamics of the upper torso, whereas the buttocks, legs and skeletal frame are treated as a lumped mass. The mass m_o is the driver's buttocks and legs supported by the seat, and the displacement (x_1–x_s) represents the displacement of the pelvis, abdomen, chest and head mass m_1 with relation to the seat.

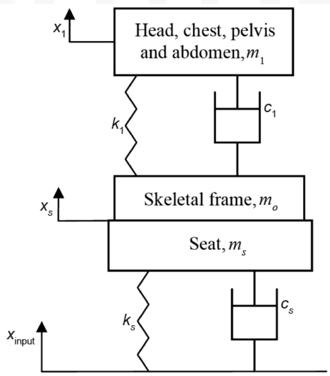

Fig. 2. Schematic of 2 DOF model by Rakheja et al.

The parameters k_1 and c_1 are the stiffness and damping coefficients of the human body model from [10]. This model can be used to predict both driving point mechanical impedance and vertical vibration transmissibility. The equations of motion for this model are identical to (1) and (2).

2.3. 3-DOF Model by Cho and Yoon (2001)

Fig. 3 shows the mass m_o, which represents the main body comprising the legs, lower torso, upper torso and arms. The mass m_1 represents the head and is connected to the main body by a neck spring k_1 and damper c_1. The main body is then connected to the hip having stiffness and damping of k_2 and c_2 respectively.

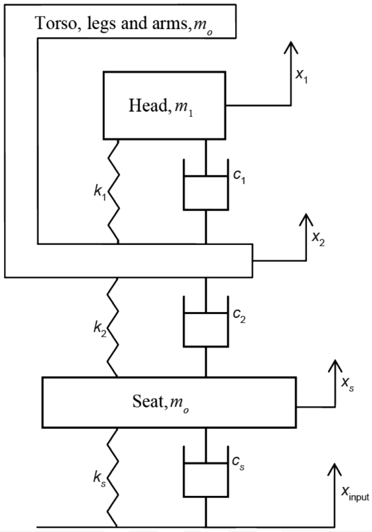

Fig. 3. Schematic of 3 DOF Model by Cho et al.

The foot is assumed negligible mass and is excluded. This model is used for vertical seat transmissibility behavior for initial seat design and excludes a backrest from [3]. The equations of motion for this model are described as (3), (4) and (5).

$$m_1 x_1 = k_1 (x_2 - x_1) + c_1 (\dot{x}_2 - \dot{x}_1) \quad (3)$$

$$m_o x_2 = k_1 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{x}_2) + k_2 (x_s - x_2) + c_2 (\dot{x}_s - \dot{x}_2) \quad (4)$$

$$m_s x_s = k_2 (x_2 - x_s) + c_2 (\dot{x}_2 - \dot{x}_s) + k_s (x_{input} - x_s) + c_s (\dot{x}_{input} - \dot{x}_s) \quad (5)$$

2.4. 3-DOF Model by Patten and Pang (1998)

Fig. 4 shows the head and neck regions, represented by mass m_1, whereas the lower torso is represented by mass m_2. Both m_1 and m_2 are connected to the seat by a rigid skeletal frame with negligible mass.

This model assumes the human is a lumped mass dispersed over the entire area of the seat cushion [8] and used to predict vibration transmissibility arising from the seat-person interface since the skeletal frame is entirely supported by the seat.

The seat-person contact area is also increased depending on the magnitude of masses m_1 and m_2. The model can be used for different types of vehicle seat suspensions and for the design of non-linear foam based seat cushions [8]. The sets of equations describing this model are presented below as (6), (7) and (8).

$$m_1 x_1 = k_1 (x_s - x_1) + c_1 (\dot{x}_s - \dot{x}_1) \quad (6)$$

$$m_2\, x_2 = k_2\left(x_s - x_2\right) + c_2\left(\dot{x}_s - \dot{x}_2\right) \tag{7}$$

$$\begin{aligned} m_s\, x_s &= k_2\left(x_2 - x_s\right) + c_2\left(\dot{x}_2 - \dot{x}_s\right) + k_1\left(x_1 - x_s\right) + \ldots \\ &\ldots + c_1\left(\dot{x}_1 - \dot{x}_s\right) + k_s\left(x_{input} - x_s\right) + c_s\left(\dot{x}_{input} - \dot{x}_s\right) \end{aligned} \tag{8}$$

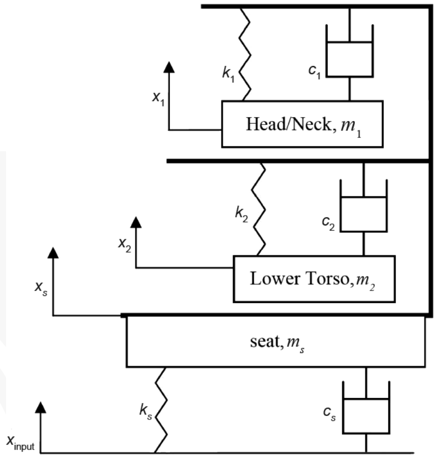

Fig. 4. Schematic of 3 DOF model by Patten et al.

2.5. 3-DOF Model proposed by Rakheja et al. (1994) and Cho et al. (2001)

Fig. 5 comprises 2 masses suspended from a common skeletal frame, representing the rigid spinal column supported by a backrest. Mass m_1 represents the pelvis and abdomen, while mass m_2 are contributions of the head and chest. Mass m_o includes the buttocks and legs, whereas the arms and feet are excluded from this model. Since mass m_o is situated directly above the seat and thigh-seat contact surface area increases, the model can predict, on a linear basis, the seat transmissibility and mechanical impedance response behaviors. A non-linear modelling strategy is recommended for the response of the cushion, especially for old seats where the cushion has bottomed out.

The set of equations describing vertical motion in the 3-DOF models proposed by Rakheja et al. and Cho et al. is presented below as (9), (10) and (11).

$$m_2\, x_1 = k_2\left(x_s - x_1\right) + c_2\left(\dot{x}_s - \dot{x}_1\right) \tag{9}$$

$$m_1\, x_2 = k_1\left(x_s - x_2\right) + c_1\left(\dot{x}_s - \dot{x}_2\right) \tag{10}$$

$$\begin{aligned} \left(m_o + m_s\right) x_s &= k_1\left(x_2 - x_s\right) + c_1\left(\dot{x}_2 - \dot{x}_s\right) + k_2\left(x_1 - x_s\right) + c_2\left(\dot{x}_1 - \dot{x}_s\right) \ldots \\ &+ k_s\left(x_{input} - x_s\right) + c_s\left(\dot{x}_{input} - \dot{x}_s\right) \end{aligned} \tag{11}$$

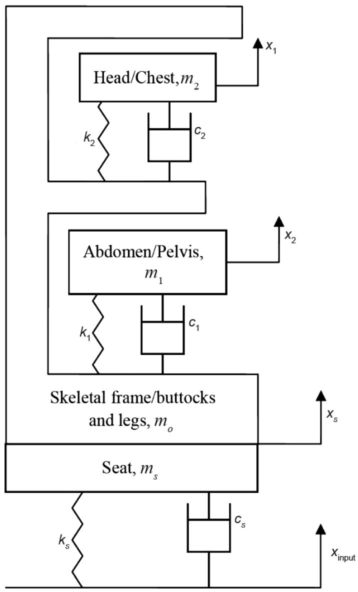

Fig. 5. Schematic of 3 DOF Model by Rakheja et al. and Cho et al.

3. Results and comparison of models

A Laplace Transform was applied to the governing equations to derive the seat to head transmissibility and mechanical impedance versus frequency. The parameters referenced in Table 1 were based on experiments related to stiffness, damping and masses of various body ligaments within the range of 44 to 76 kg. The seat stiffness, mass and damping values from [4] were made constant for all models in order to compare vertical transmissibility and mechanical impedance behavior for the various biodynamic models and experimental results.

Table 1

Biodynamic parameters for mass, stiffness and damping

Model Description	Mass [kg]	Stiffness [kN/m]	Damping [kNs/m]
2 DOF by Griffin (1990)	m_s =1, m_o = 8.7, m_1 = 66.3	k_s =120, k_1 =39.7	c_s = 3.23, c_1 = 1.36
2 DOF by Rakheja et al. (1994)	m_1 = 52.9, m_o = 22.1	k_1 = 27.95	c_1 = 0.5
3 DOF by Cho et al. (2001)	m_1 = 7.3, m_o = 67.7	k_1 = 41, k_2 = 74.3	c_1 = 0.32, c_2 = 2.81
3 DOF by Patten et al. (1998)	m_1 = 12.5, m_2 = 62.5	k_1 = 24, k_2 = 68	c_1 = 0.19, c_2 = 1.54
3 DOF by Rakheja et al. (1994) and Cho et al. (2001)	m_o = 22.06, m_1 = 8.82, m_2 = 44.1	k_1 = 23.3, k_2 = 14.73	c_1 = 0.36, c_2 = 0.15

The derived seat to head transmissibility versus frequency curves with three resonant frequencies occurring at 3.5 Hz, 5 Hz and approximately 6.3 Hz are shown in Fig. 6, and their mathematical relationship is described in [1].

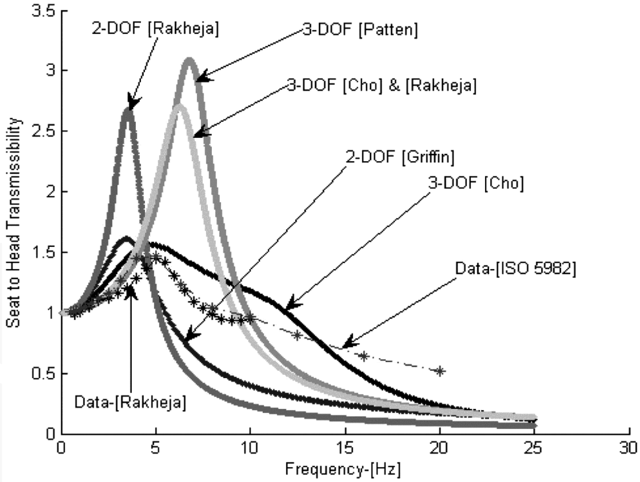

Fig. 6. Seat to head transmissibility as a function of frequency for the analyzed models

The 2-DOF curves have a common resonant frequency occurring at about 3.5 Hz, although there is considerable difference between the two peak seat to head transmissibility magnitudes due to the stiffness parameters. The 3-DOF by Patten, 3-DOF by Rakheja and Cho curves have similar seat to head transmissibility at 6.8 Hz and 6.3 Hz respectively that depict whole body resonant frequency. The 3-DOF by Cho and experimental curves from ISO Standard [5] have similar seat to head transmissibility response and a common peak resonant frequency occurring between 4–5 Hz. Published experimental data from ISO and Rakheja et al. have been used to simulate the seat to head ratio and mechanical impedance responses without the use of a backrest support.

Similarity of the peak seat to head transmissibility magnitude and resonant frequency in the 3-DOF by Patten, 3-DOF by Rakheja and Cho, and 2-DOF curves are influenced by the seat configuration and backrest support described in [3]. The 3-DOF by Patten whole body vibration frequency of 6.8 Hz derived from the seat to head transmissibility is slightly higher than the experimental results since the biodynamic model described in Fig. 4 includes only the head and neck region as a lumped mass supported by the seat backrest.

The 3-DOF by Rakheja and Cho curve is similar to the 3-DOF by Patten curve, although occurring at a lower peak magnitude, due to the mass of the head and chest regions approximated as a single lumped mass together with lower stiffness and damping parameters. The 3-DOF by Cho curve is able to approximate published experimental seat to head transmissibility data, since the model excludes the use of a backrest support. The inclusion of a backrest increases the natural frequency of the seated person when compared to a seat without a backrest from [3]. It can thus be seen that the 2-DOF and 3-DOF by Cho whole body frequencies are lower compared to the other models.

Mechanical impedance described by [4] is the ratio of the driving force acting on a system to the resulting velocity of the system measured at the same point and in the same direction as the applied force with units of [Ns/m]. A similar definition by [9] suggests the mechanical impedance is the force per unit velocity directed towards the person, which originated from the seat-person interface. The impedance response behavior is a "to the body" type transfer function, whereas the vibration transmissibility is construed as vibration transmission "through the body". The mechanical impedance curves expressed as a function of frequency are shown in Fig. 7.

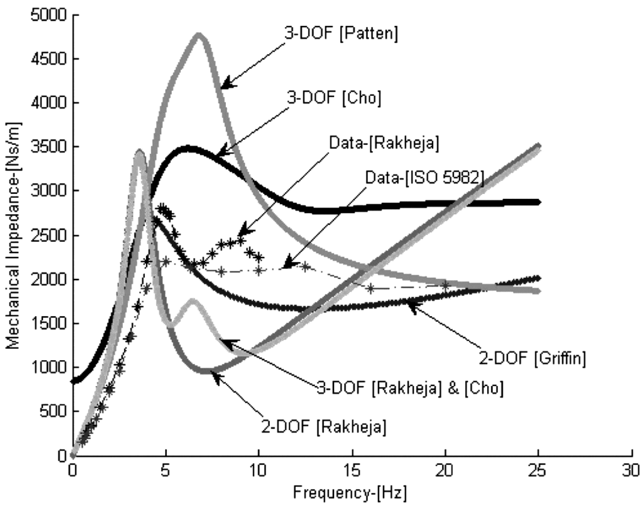

Fig. 7. Mechanical impedance curves as a function of frequency for the analyzed models

All mechanical impedance curves approximate the whole body resonant frequency occurring within the region of 4.5–6.8 Hz. The 3-DOF by Rakheja and Cho, 2-DOF by Rakheja and 3-DOF by Cho curves show similar peak impedance magnitudes, whereas the 3-DOF by Patten curve has a higher peak impedance magnitude. The 3-DOF by Rakheja and Cho curve highlights a second resonant frequency region, which are not replicated in other models, but supported with experimental data and associated with motion of the legs.

The 2-DOF by Rakheja and 3-DOF by Rakheja and Cho curves have similar impedance responses, which have a lower resonant frequency value, compared to the other curves. The similarity in the impedance response is due to the approximately equal mass distribution of the lower skeletal frame occurring at the seat-person interface. The high peak impedance and transmissibility magnitudes observed in the 3-DOF by Patten model are caused by the high stiffness parameters with similar findings supported by Smith [12]. Experimental data shown in Fig. 7 is closely approximated using a 4-DOF model that was described in [5] together with the 2-DOF by Griffin curve. The results indicate that the used biodynamic stiffness and damping parameters represent a compromise in accuracy towards achieving both mechanical impedance and seat to head transmissibility responses.

4. Conclusion

The five biodynamic models provide an easy method to determine peak seat to head transmissibility and mechanical impedance behaviors when compared to experimental results. As an initial design approximation to the seat suspension system, the 2-DOF models could be utilized to predict the discomfort level or peak transmissibility and impedance magnitude arising from the seat cushion-person interface and lower torso. The 3-DOF models can be used to investigate the transmissibility effects relating to the skeletal frame, whole body vibration and to reconfirm the discomfort level relating to the lower torso in addition to investigating the use of a backrest.

The reason why the 2-DOF models give results closest to the experimental data is due to the exclusion of the backrest support and absence of greater anatomical description related to the legs and feet. The 3-DOF model is sensitive to the backrest support and thus a higher resonant frequency is observed for whole body vibration. The effect of various backrest support positions and its influence on vibration transmissibility and whole body vibration is a subject of future research.

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