

An Improved Human Biodynamic Model Considering the Interaction between Feet and Ground

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ABSTRACT

Nowadays, studying the human body response in a seated position has attracted a lot of attention as environmental vibrations are transferred to the human body through floor and seat. This research has constructed a multi-body biodynamic human model with 17 degrees of freedom (DOF), including the backrest support and the interaction between feet and ground. Three types of human biodynamic models are taken into consideration: the first model doesn't include the interaction between the feet and floor, the second considers the feet and floor interaction by using a high stiffness spring, the third one includes the interaction by using a soft spring. Based on the whole vehicle model, the excitation to human body through feet and back can be obtained by ride simulation. The simulation results indicate that the interaction between feet and ground exerts non-negligible effect upon the performance of the whole body vibration by comparing the three cases.

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INTRODUCTION

Many occupational workers are exposed to whole-body vibration in road or off-road vehicles. People are continuously exposed to vibrations during travelling which cause an adverse effect on the human body. The human body is really sensitive to whole body vibration. There are various factors including road irregularities, vehicle suspension, vehicle dynamics, tires, seat design, and the human body's properties, which affect this vibration transmission to human body. The ride comfort is influenced by the exposure duration, amplitude, and frequency of vibration to a human body[1]. While seated, the human body is The most sensitive vibrations of the human body are at 4-10 Hz in vertical direction and 0.5-3 Hz in horizontal direction. Engineers evaluate the ride comfort on the road or in a lab road test simulator[2]. The human body can be considered as a dynamic system whose mechanical properties vary with respect to time and body components.

Different experimental methods have been used in the automobile industries to measure vibration exposure in vehicles. These methods are expensive and not effective because each human body's sensitivity to the same vibration is different. Over the past few years, researchers developed different mathematical models to study human body response to whole-body vibration. These models can be divided into three larger groups as lumped parameter model, finite element

model, and multi-body model. In the lumped parameters models, human body is represented by a set of masses interconnected by spring and dampers. However, these models are used to study human body response only in vertical direction. Finite element models can be used to analyze human body response with high precision but they are computational expensive. Through the use of multi-body models, it is easy to study how a human body response to different types of inputs. Hence, there is a need for developing good models of seat-occupant systems which can be used to predict body response in different directions like horizontal, vertical, and rotational directions.

The multi-body human model includes several rigid bodies connected by pins or balls with bushing elements to represent rotational and translational motions. Ippili et al.[3] developed a simplified 2-D, multi-degree model of a seat-occupant system which consisted of three interconnected (pinned) planar rigid bodies. In this model, head is not modeled. Cho et al.[4] developed a 9 DOF model having three rigid bodies counting the seating posture with the backrest support. From the measured whole-body vibration responses, they found that it is important to include the backrest support into the model as the backrest support increases the natural frequency significantly. Kim et al.[5] worked on the development of a biomechanical model of the human body for evaluating the vibration transmissibility and dynamic response to vertical vibrations in sitting posture. Their human body

model has 5 mass elements each representing legs with feet, pelvis, torso, head and viscera of the human body. Liang et al.[6] studied the biodynamic response for different postures along with and without backrest support with a multi-body model. Kumbhar et al.[7] used one linear 14-degree of freedom (DOF) multi-body biodynamic model from literature for evaluating three different seats based on human responses. Backrest support and feet contact were included in the model because a considerable amount of vibrations is transferred through it. Kumbhar et al.[8] used an optimization-based method to determine the optimal seat dynamic parameters for seat suspension, and cushion based on minimizing occupant's body fatigue (occupant body absorbed power). Deb et al.[9] developed a 7-DOF occupant model and coupled with the 13-DOF vehicle model to ride comfort analysis. But the proposed model is lumped parameter model. In many literatures, human dynamic models and the body response to whole body vibration has been discussed, but the feet contact with the ground has not been included. The objective of this study is to investigate the effect of the interaction between the feet and floor on human body response under whole body vibration.

This paper is organized as follows: human biodynamic model will be first introduced and combined with a whole vehicle. Then the absorbed power calculation for human body components will be explained followed by simulations of the human vehicle system. Finally it gives conclusions and discussions.

HUMAN BIODYNAMIC MODEL

In this study, a 23-degree of freedom (DOF) dynamic model of a seat-occupant system which includes a 17-DOF human biodynamic model and a 6-DOF seat model is constructed in ADAMS from literature[7]. In literature[7], the human biodynamic model had 14-DOF because lower legs and feet were combined with thighs as a part. In this paper lower legs are separated from thighs and are combined with feet only. This adds 3 DOFs and the total human model has 17 DOFs in Figure 1. As shown in this figure, the human body model includes 6 body elements. Mass m_1 represents the thighs, mass m_2 represents the pelvis, mass m_3 represents the torso, mass m_4 represents the head, and mass m_5 represents viscera, mass m_6 represents legs and feet of the human body. Table 1 shows mass and inertial properties and different center of gravity locations. These coordinates are defined as the human body mode in seated position in which the body is in contact with the seat, with backrest support (backrest angle is 2 degrees), and the feet are supported on the floor. This model considers vibrations transferred through seat, the backrest support, and the feet.

Each mass (from m_1 to m_4 , and m_6), except the mass of the viscera (m_5), has 2 translational motions (one horizontal and one vertical) and one rotational motion, and the mass of the viscera (m_5) has only 2 translational motions. Overall, this human model has 17 DOFs. Points marked as G_i ($i=1$ to 6) are the mass center of gravity points of each elements. All masses except mass m_5 are connected to each other by a bushing element. J_i ($i=1$ to 4) are the locations of these bushing elements representing joints in between two adjacent bodies. They are actually connected by translational and torsional sets of springs (K , K_{pi}) and dampers (C , C_{pi}). The mass of the viscera (m_5) is tilted at an angle β with the horizontal direction, angle γ with the

vertical direction, as shown in figure 2, due to an inclined backrest angle (21 degrees). In this figure, contact between the seat and each body is represented by one point in each body c_i ($i=1$ to 3) to simplify the force calculations. So c_1 and c_2 are the contact points of body 1 and 2 with the seat cushion respectively, and c_3 is the contact point of body 3 with the backrest cushion. The horizontal (K_{hi} , C_{hi}) and vertical (K_{vi} , C_{vi}) spring and damper under each mass represent the stiffness or flexibility of that body segment mass. For example, the horizontal (K_{h1} , C_{h1}) and vertical (K_{v1} , C_{v1}) spring and damper represent the stiffness or flexibility of body 1 (m_1) with the seat contact. Values for all parameters are selected from literature [7] and summarized in Table 2. The values of these seat parameters are estimated based on measurement of floor and hip acceleration on dummy model under random vertical and fore-aft vibrations of 1.0 m/s² in the frequency range of 1-25 Hz. To study the effect of feet contact on body response under whole body vibration, the seat-occupant system model has three cases in Figure 3. In Case 1 the feet do not contact with the floor; in Case 2 and Case 3 the contact between feet and floor is modeled by the horizontal (K_{h6} , C_{h6}) and vertical (K_{v6} , C_{v6}) spring and damper in ADAMS.

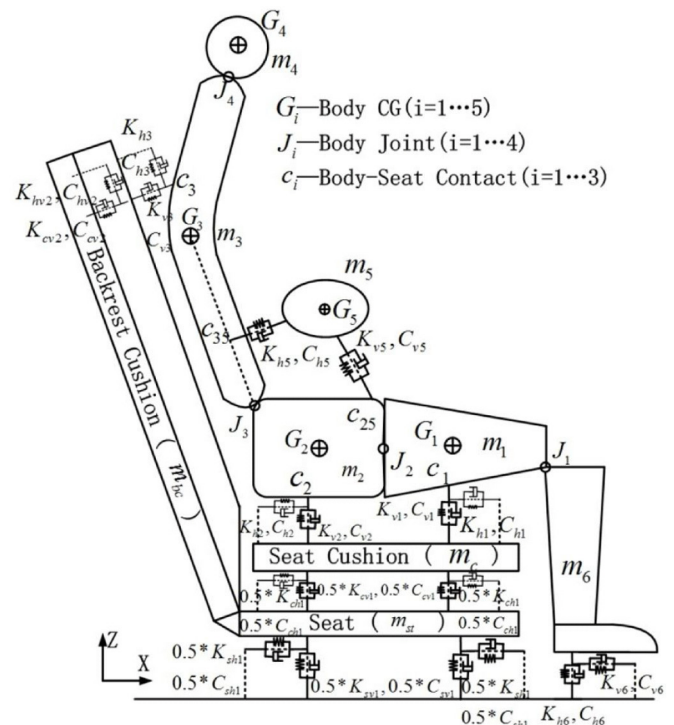


Figure 1. seat-occupant dynamic model

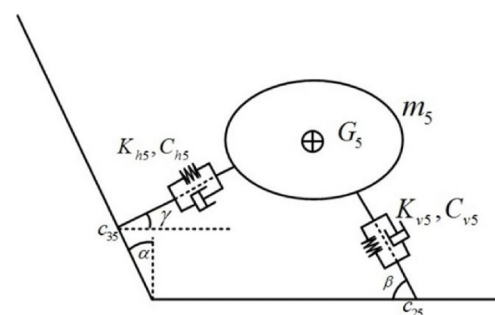


Figure 2. Spring and damper angles

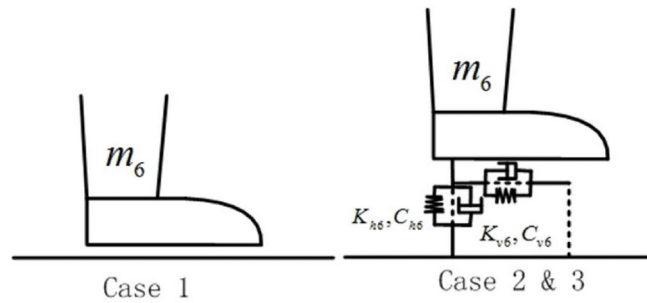


Figure 3. Mechanical relationship of feet and ground for three cases

Table 1. Human body mass, inertial properties and geometry parameters

Body Properties				Body Location (X, Z), (mm) with backrest support		
Body	Mass(Kg)	Body	Inertia(Kg·m ²)	C.G. location	Joint Location	Seat Contact
m_1	20.0	I_1	1.16	G_1 (133, 70)	J_1	c_1 (133,0)
m_2	11	I_2	0.68	G_2 (-23, 97)	J_2	c_2 (-19,0)
m_3	19.87	I_3	1.53	G_3 (-152.3, 471.6)	J_3	c_3 (-147.3, 379.3)
m_4	7.25	I_4	0.402	G_4 (161.5, 720.9)	J_4	-
m_5	12.9	-	-	G_5 (-65.9, 250.9)	-	-
m_6	0.3	-	-	-	-	-

Table 2. Biomechanical properties of human body model

Human Body Biomechanical Properties					
Spring Stiffness	Notations	Value	Damping Coefficient	Notations	Value
Horizontal stiffness of Body 1	K_{h1}	614	Horizontal damping of Body 1	C_{h1}	14
Vertical stiffness of Body 1	K_{v1}	16710	Vertical damping of Body 1	C_{v1}	8010
Horizontal stiffness of Body 2	K_{h2}	905	Horizontal damping of Body 2	C_{h2}	15
Vertical stiffness of Body 2	K_{v2}	121300	Vertical damping of Body 2	C_{v2}	47
Horizontal stiffness of Body 3	K_{h3}	17200	Horizontal damping of Body 3	C_{h3}	334.5
Vertical stiffness of Body 3	K_{v3}	2300	Vertical damping of Body 3	C_{v3}	154
Horizontal stiffness of Body 5	K_{h5}	1930	Horizontal damping of Body 5	C_{h5}	79
Vertical stiffness of Body 5	K_{v5}	18370	Vertical damping of Body 5	C_{v5}	197
Translational stiffness of Joint 1	K_1	23550	Translational damping of Joint 1	C_1	154
Translational stiffness of Joint 2	K_2	6400	Translational damping of Joint 2	C_2	61
Translational stiffness of Joint 3	K_3	299	Translational damping of Joint 3	C_3	1790
Translational stiffness of Joint 4	K_4	113700	Translational damping of Joint 4	C_4	66
Rotational stiffness of Joint 1	K_{r1}	220	Rotational damping of Joint 1	C_{r1}	104
Rotational stiffness of Joint 2	K_{r2}	162	Rotational damping of Joint 2	C_{r2}	30
Rotational stiffness of Joint 3	K_{r3}	328	Rotational damping of Joint 3	C_{r3}	724
Rotational stiffness of Joint 4	K_{r4}	915	Rotational damping of Joint 4	C_{r4}	340
Translational stiffness: N/m, Translational damping: N-s/m, Rotational stiffness: N-m/rad, Rotational damping: N-ms/rad					

A 17-DOF biodynamic human model is placed on a seat with a seat cushion, backrest cushion and seat suspension as shown in Figure 1. The total DOF of seat-occupant system is 23, by considering 2 DOFs of the seat, 2 DOFs of the each cushion. In Figure1, m_{st} is the mass of

seat suspension, m_c is the mass of seat cushion, and m_{bc} is the mass of seat cushion. The seat-occupant system modeled in ADAMS is represented in Figure 4.

Spring and damper parameters for the interaction between Body 6 and the floor are summarized in Table 4.