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Modeling of a Seated Human Body Exposed to Vertical Vibrations in Various Automotive Postures

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Abstract: Although much research has been devoted to constructing specific models or to measuring the response characteristics of seated subjects, investigations on a mathematical human model on a seat with a backrest to evaluate vehicular riding comfort have not yet attracted the same level of attention. For the responses of a seated body to vertical vibrations, mathematical models of the mechanisms must be at least two-dimensional in the sagittal plane. In describing the motions of a seated body, two multibody models representative of the automotive postures found in the literature were investigated, one with and the other without a backrest support. Both models were modified to suitably represent the different automotive postures with and without backrest supports, and validated by various experimental data from the published literature pertaining to the same postural conditions. On the basis of the analytical study and the experimental validation, the fourteen-degrees-of-freedom model proposed in this research was found to be best fitted to the test results; therefore, this model is recommended for studying the biodynamic responses of a seated human body exposed to vertical vibrations in various automotive postures.

Key words: Multibody models, Sagittal plane, Backrest support, Biodynamic responses, Automotive postures

Introduction

In a seated posture, humans are most sensitive to whole-body vibrations under low-frequency excitation; therefore, biodynamic responses of a seated human body when exposed to vertical vibrations have attracted much attention through the years. Moreover, knowledge of the human responses to vibrations requires an understanding the cause-effect relationships among the transmission of vibrations through the body and its health, comfort and performance. These responses have been widely assessed in terms of seat-to-head (STH) transmissibility, driving-point mechanical (DPM) impedance, and apparent (AP) mass. The first function refers to the transmission of motion through the body; whereas the other two pertain to the force and motion at the point of vibration input.

The human body is a very sophisticated dynamic system whose mechanical properties vary from one moment to another and from one individual to another. From the results of a large amount of experimental data, various biodynamic models have been developed to describe human motion. According to different techniques, these models can be grouped as lumped-parameter (LP), finite-element (FE), and multibody (MB) models.

An LP model consists of lumped masses, springs and dashpots[1–14]. A variety of experiments have also been implemented by various researchers under widely varying testing conditions, involving vibration excitations, postural constraints, and subject populations. These have, therefore, resulted in significant variations between the different data sets generated. In an effort to define generalized values for characterizing the biodynamic responses of a seated body in the most commonly encountered work environments, Boileau *et al*.[15] identified STH transmis-

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sibility, DPM impedance, and AP mass from the existing published data by synthesizing and creating envelopes from the various data sets selected. The values of the different biodynamic functions were defined for subjects maintaining an erect seated posture without backrest support, with their feet resting on a vibrating platform. In addition, a thorough study of LP models of seated subjects exposed to vertical vibrations without backrest support was conducted by Liang and Chiang[16]. All models were systematically analyzed and validated by a synthesis of various experimental data from the published literature. Some LP models were further modified to represent a pregnant body and integrated with a vehicle model to assess the biodynamic responses of seated pregnant subjects exposed to vertical vibrations in driving conditions[17].

Some FE (sometimes called distributed-parameter) models treat the spine as a layered structure of rigid elements representing vertebral bodies and deformable elements characterizing intervertebral discs. The FE method has been used to model spine, viscera, head, pelvis and buttocks tissues by using beam, spring and mass elements in a two-dimensional (2-D) plane[18, 19]. With the incorporation of certain powerful FE programs, such as LS-DYNA, this kind of model is in widespread use in vehicle crashworthiness and injury assessment of human impacts[20, 21].

MB models consist of several rigid bodies interconnected by bushing elements (rotational and translational spring-damper units), pin (2-D) and/or ball-and-socket (3-D) joints. The 3-D models are often used in the study of human exercise and injury assessment in a vehicle crash[22–24]. Some are also applied to study the biodynamic responses of the human body[25]. For the responses of a seated body exposed to vertical vibrations, mathematical models must be at least 2-D in the sagittal plane. Especially in an automotive seating environment, bouncing and pitching motions are the major concerns in vehicle riding assessment. As a result, a few 2-D models approach minimal satisfaction of the aforementioned requirements[26–31].

From the foregoing literature review, it is obvious that the LP model is probably one of the most popular analytical methods for the study of biodynamic responses of a seated body. This model is simple and easy to implement; however, it is limited to 1-D analysis. The FE and 3-D MB models, being too complex to apply in dynamic simulations, also require knowledge of the mechanical properties of a seated body and measurements of dynamic response data, which have been difficult to achieve. Moreover, the dynamic responses of a seated body with backrest support, similar to those in automotive seating environments, are quite different from those without such support. The contribution of back response is of importance in the evaluation of the riding quality of a vehicle, being reflected in the weighting function and axis-multiplying factor defined by the International Standardization Organization (ISO) in regulation 2631-1[32]. Therefore, this research is devoted to a thorough survey of the literature on 2-D MB models having appropriate complexity to represent a seated body. Two representative models, one proposed in this research and modified from the one developed by Kim *et al.*[31] and the other constructed by Cho and Yoon[28], are investigated. Both models are modified to suitably represent the different automotive postures with and without backrest supports. An analytical study is first implemented for each model to derive the system equations of motion (EOMs). The simulations of dynamic responses for both models are then validated by the various test data of vertical vibration responses available in the published literature. On the basis of the analytical study and the experimental validation, the model best fitted to the experimental results will be recommended for the study of the biodynamic responses of a seated human body in different automotive postures when exposed to vertical vibrations.

Measurements and Mathematical Models

As previously mentioned, through the years many mathematical models for the study of biodynamic responses of a seated human body have been published on the basis of individual test data. As part of this study, the basic assumptions and experimental data for the analysis of seated humans exposed to vertical vibrations will first be identified. Moreover, two MB models, having nine and fourteen degrees of freedom (DOFs), respectively, will be illustrated and summarized in this section of study.

Basic assumptions

The biodynamics of seated human subjects exposed to vertical vibrations has been widely assessed in terms of STH transmissibility, DPM impedance, and AP mass. The first function refers to the transmission of motion through the body; whereas, the other two pertain to the force and motion at the point of vibration input to the body. To satisfy the objectives for this research, three different sets of experimental data used to characterize the aforementioned response functions are summarized as follows.

(1) Measurements without backrest support

A variety of test data used to characterize the biodynamic response functions has been established by using widely varied testing conditions, most of which can be grouped in the data sets for a seated body without backrest support. Such grouping has resulted in considerable discrepancies among the data. To avoid these discrepancies, a preliminary conclusion was reached that any attempt to define generalized values might not be appropriate unless it could be defined specifically for a particular application or within a limited but well-defined range of situations. From the literature review, data sets satisfying the following requirements were thus selected for the synthesis of biodynamic characteristics of seated human subjects[15]:

- Human subjects were considered to be sitting erect without backrest support, regardless of the position of the hand;
- Body masses were limited to the range within 49–94 kg;
- The feet were supported and vibrated;
- Data sets acquired under vibration excitations were constrained to the vertical direction;
- Vibration excitation amplitudes were below 5 m/s^2, the nature of excitation being specified as either sinusoidal or random;
- The excitation frequency range was limited to 0.5–20 Hz;

With these assumptions, the experimental data are summarized in Table 1[15].

(2) Measurements with backrest inclined 21°

From 10 subjects having an average mass of 61.1 kg, measurements of 3 transmissibility values were implemented at different locations on the respective bodies seated with backrests inclined 21°. This set of experimental data was used mainly to validate the MB model developed by Cho and Yoon[28]. In this study only the STH transmissibility data were selected to validate the targeted MB models to avoid inappropriate comparisons of the response function from simulations, as shown in Table 2[28].

(3) Measurements with backrest inclined 12°

Measurements of the biodynamic response characteristics of 27 subjects exposed to vertical vibrations under 36 different sitting postures were conducted. The mean body mass of the participants was 70.8 kg. The results suggest that the position of the hands (on the lap or on the steering wheel), the back-support condition, and the body mass will affect the test results of apparent mass on the seat pan. The influence of the seat pan inclination was observed to be negligible for the range investigated (7.5°). Because of an incomplete knowledge of the mechanical properties of the body, the effect of hand positions and body mass on AP mass is difficult to determine. This research is focused only on the effect of the backrest angle on the biodynamic response functions. The AP mass values measured at three different back-support positions, representing a flat pan with the back unsupported (NVF), and with the back supported by a vertical backrest (BVF) or an inclined backrest (BIF), were scaled, as summarized in Table 3[33].

Mathematical models

In MB models, a human body in various sitting pos-

Table 1. Experimental results: seated human body exposed to vertical vibrations without backrest support[15]

Frequency	STH transmissibility			AP mass (kg)		
	Lower limit	Mean	Upper limit	Lower limit	Mean	Upper limit
0.5	1.00	1.01	1.02	58.7	61.2	65.9
0.63	1.00	1.01	1.02	58.0	61.4	65.8
0.8	1.00	1.01	1.02	53.8	60.6	65.6
1.0	1.01	1.02	1.03	49.8	59.6	65.2
1.25	1.02	1.03	1.06	46.9	59.2	65.2
1.6	1.02	1.06	1.14	48.5	60.0	66.7
2.0	1.03	1.08	1.16	49.0	60.8	70.6
2.5	1.04	1.10	1.15	51.2	62.6	75.2
3.15	1.11	1.16	1.22	56.0	70.7	85.6
4.0	1.16	1.29	1.36	61.0	79.3	94.6
5.0	1.28	1.45	1.56	52.8	74.5	92.3
6.3	0.99	1.23	1.44	41.9	53.2	61.9
8.0	0.87	1.01	1.28	31.9	38.5	47.4
10.0	0.86	0.96	1.08	27.8	31.5	36.1
12.5	0.74	0.86	0.99	23.4	25.9	29.8
16.0	0.55	0.71	0.89	17.0	17.4	17.8
20.0	0.40	0.63	0.84	12.5	14.1	16.9

Table 2. Experimental results: seated human body exposed to vertical vibrations with backrest support (Seat pan angle: 0°, Backrest angle: 21°)[28]

Frequency (Hz)	STH Transmissibility	Frequency (Hz)	STH Transmissibility	Frequency (Hz)	STH Transmissibility
2.0	1.0947	4.3	3.1832	7.5	1.0000
2.2	1.1263	4.5	2.9053	8.0	0.9608
2.4	1.1895	4.4	3.0644	8.5	0.8382
2.6	1.2737	4.6	2.7053	9.0	0.7892
2.8	1.4000	4.7	2.5000	9.5	0.7059
3.0	1.5798	4.8	2.2500	10.0	0.6324
3.1	1.7394	4.9	2.0365	10.5	0.5539
3.2	1.9628	5.0	1.8617	11.0	0.5000
3.3	2.1719	5.2	1.5372	11.5	0.4681
3.4	2.2917	5.4	1.2526	12.0	0.4309
3.5	2.4062	5.6	1.0842	13.0	0.4043
3.6	2.5000	5.8	0.9510	14.0	0.3404
3.7	2.7211	6.0	0.9118	15.0	0.3191
3.8	2.8947	6.2	0.8824	16.0	0.2926
3.9	3.0792	6.4	0.8627	17.0	0.2500
4.0	3.1733	6.6	0.8922	18.0	0.2340
4.1	3.2178	6.8	0.9167	19.0	0.2181
4.2	3.2223	7.0	0.9657	20.0	0.2181

Table 3. Experimental results: seated human body exposed to vertical vibrations with backrest support (Seat pan angle: 0°, Backrest angle: 12°)[33]

NVF				BVF				BIF			
Hz	AP mass	Hz	AP mass	Hz	AP mass	Hz	AP mass	Hz	AP mass	Hz	AP mass
0.25	56.36	12.743	35.28	0.25	57.51	12.793	39.37	0.25	57.60	15.267	36.10
1.075	60.00	13.762	32.25	1.366	66.00	13.779	36.36	1.556	59.79	16.311	32.98
1.775	63.86	14.757	29.30	2.39	63.39	14.789	33.43	2.526	63.07	17.354	30.00
2.500	67.93	15.873	26.62	3.098	67.40	15.731	29.86	3.112	67.14	18.398	26.88
3.350	71.59	16.910	23.80	3.634	71.49	16.745	26.92	3.699	71.36	19.636	24.82
3.850	75.52	18.020	21.97	4.0	75.85	17.877	24.34	4.107	75.64	20.897	22.91
4.125	79.72	19.363	20.77	4.244	80.49	19.127	22.17	4.337	80.00	22.205	20.78
5.096	91.77	20.675	18.83	4.61	84.69	20.172	20.56	4.821	84.26	23.538	19.31
5.673	88.16	22.644	18.48	5.0	88.95	21.576	19.07	5.735	86.81	24.923	17.85
5.913	83.61	23.600	17.66	5.892	87.83	23.005	18.01	6.495	83.69	26.158	17.37
6.106	79.10	25.000	16.62	6.362	83.57	24.384	16.62	6.985	79.21	27.35	16.33
6.322	74.83	26.316	16.28	6.643	79.10	25.651	16.16	7.402	75.07	28.695	15.43
6.514	70.41	27.703	15.45	6.925	74.81	26.86	15.76	7.745	70.79	29.852	14.74
6.779	66.14	29.115	14.69	7.277	70.38	28.233	14.77	8.088	66.50	31.225	14.05
6.923	61.72	30.625	14.69	7.571	65.95	29.698	14.44	8.309	62.07	32.623	13.43
7.308	57.64	32.019	13.86	7.911	61.66	31.051	13.64	8.652	57.81	33.652	12.60
7.572	53.47	33.365	13.17	8.122	57.44	32.5	12.91	9.387	54.18	34.877	13.15
8.125	49.56	35.0	13.17	8.592	53.51	33.364	12.85	10.32	50.75	36.049	12.60
8.726	45.93	36.34	12.41	9.178	49.38	34.673	12.85	11.3	48.01	37.122	12.73
9.808	43.10	37.464	12.76	10.21	47.21	36.071	12.32	12.35	45.00	38.537	13.36
10.66	40.61	38.708	12.41	11.15	44.85	37.143	12.32	13.5	42.53	39.683	11.35
11.89	37.82	40.0	11.66	12.0	42.10	40.0	12.32	14.34	39.08	40.0	11.35

tures is often modeled as a mechanical system composed of several rigid bodies interconnected by translational and/or rotational spring-damper units. Mathematical models can have various structures, depending on the application requirements. In this research, two different MB models with suitable complexity were selected from the published literature to study the biodynamic responses of a seated human body exposed to vertical vibrations in various automotive postures.

(1) Cho's model[28)]

Developed by Cho and Yoon[28)] in 2001, a model of a seated body was constructed with 3 rigid segments in a 2-D sagittal plane, with a seated mass of 56.8 kg. In this model the mass segments are connected by bushing elements to represent mechanical properties of the vertebral column. The lower body m_1 represents the sacrum and legs; whereas, the upper body m_2 includes the trunk plus the arms, and the mass m_3 denotes the head. The vertical and horizontal springs and dampers under m_1 and m_2 are used to characterize both the deformable properties of the pelvis and thighs and the contacting properties of the back with a rigid seat. To closely simulate automotive sitting environments, three vertical and horizontal spring-damper units representing the mechanical properties of seat and backrest cushions are serially connected to those under m_1 and m_2. In this model, the foot support is ignored, because the vibration input through it is small. To simplify the computations, the EOMs were linearized by taking the Taylor series expansion at static equilibrium positions with respect to the variables to be obtained. Therefore, the model is linear with 9 DOFs. Mass and inertial properties were obtained from anthropometric data in the literature; whereas, the joint and contact positions were measured directly from the subjects. The mechanical properties were determined by matching the measured transmissibility values at different locations of the seated body through an optimization procedure. The schematic and biomechanical parameters of the model are illustrated in Fig. 1(a) and Table 4.

(2) Proposed model

Originally developed by Kim *et al.*[31)] in 2006, the proposed model was composed of 5 rigid segments in a 2-D sagittal plane, with a total mass of 71.32 kg. Similar to Cho's model, most rigid segments are connected to each other by bushing elements, except for m_5 (viscera) which is connected to m_2 (pelvis) and to m_3 (torso) by vertical and horizontal spring-damper units, respectively. Since the mass m_5 allows no rotational motion, the model has 14 DOFs. The springs and dampers under m_1 (thighs) and m_2 represent the deformable properties of the pelvis and thighs. The foot support or the vibration input through it is included in the model, but not for back support. Therefore, the model is limited to an erect sitting posture without backrest support, unless certain modifications are made. The mass and inertial properties as well as the joint and contact positions were obtained from anthropometric data in the literature; whereas, the mechanical properties were determined by matching the individual measurements of STH transmissibility and AP mass through an optimization procedure. Since the original model by Kim *et al.*[31)] is nonlinear in natural, an adaptive-step-size fourth-order Runge-Kutta algorithm is used to solve the system EOMs. As dynamic problems of this sort can be discussed in a linear range, Kim's model is simplified by taking the Taylor series expansion of the EOMs at static equilibrium positions with respect to design variables. The proposed model is hence linear. Moreover, to make the proposed model more extensively applicable, a backrest support is added by a method similar to that in Cho's model. The mechanical properties were determined by first matching the experimental data listed in Table 1 for the case without a backrest, and then fitting the data provided in Table 2 for the case with a backrest inclined 21°. The schematic and biomechanical parameters of the proposed model are illustrated in Fig. 1(b) and Table 5.

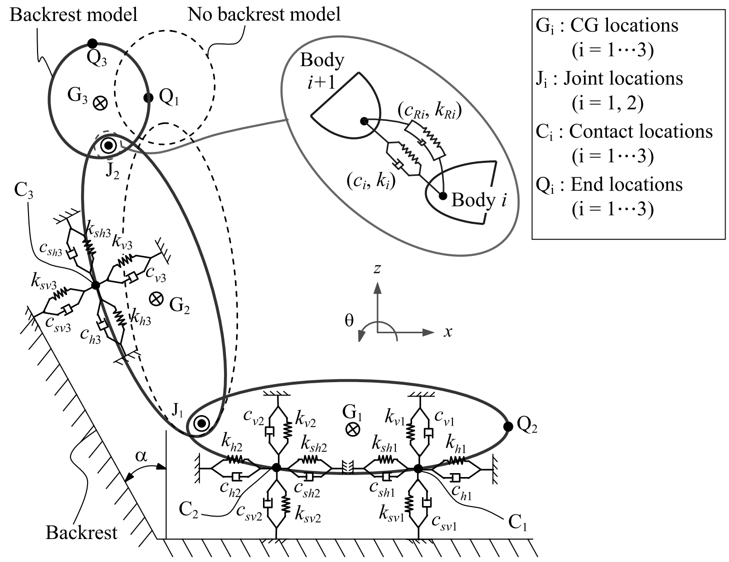
Through the aforementioned discussion, the construction and relations of all mathematical models and corresponding experimental data to determine the mechanical properties are summarized in Table 6.

Analytical Study

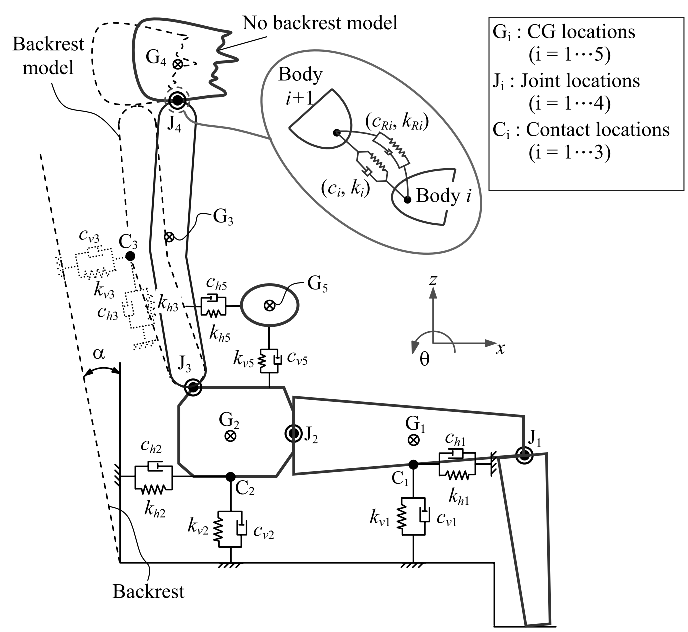
As previously mentioned, the experimental studies on the biodynamics of a seated human body exposed to vertical vibrations have been widely assessed in terms of STH transmissibility, DPM impedance, and AP mass. Moreover, the backrest in automotive seating environments contributes to decrease muscle tensions and maintain sitting posture during driving[28)]. Therefore, the responses of a seated body both with and without backrest supports will be analyzed in the following discussion.

Derivation of system EOMs

In the preceding discussion, the parameters for Cho's model listed in Table 4 considered both the backrest support and seat properties; whereas, those for the proposed model in Table 5 are in an erect sitting posture, with a vertical and rigid backrest. To be consistent in comparison, both models must be adjusted to adequately represent the seated body with and without backrest support in the simulations. In the modification of Cho's model, to represent the seated body in a normal sitting posture without backrest support, the upper body m_2 is assumed to be



(a) Cho's model



(b) Proposed model

Fig. 1. The MB models of a seated human body exposed to vertical vibrations.

rotated clockwise at an angle of 21° with respect to hip joint J_1, and the head is kept in the original posture. Therefore, the head mass m_3 moves only in the *x-z* plane without rotation. The back support (k_{v3}, c_{v3}, k_{h3} and c_{h3}) as well as the seat and back cushion properties (k_{svi}, c_{svi}, k_{shi} and c_{shi}, i = 1–3) are removed from the original model. The simulations for the modification of Cho's model and for the proposed model without backrest are compared by STH transmissibility and AP mass, as listed in Table 1. Similarly, the proposed model is adjusted by rotating the upper body m_3 and viscera m_5 counterclockwise relative to the S1-L5 joint (J_3) to represent the body seated at a 21°-backrest posture. The head mass m_4 also remains in the same posture but moves a distance according to the C7 joint (J_4). The backrest support is added at the T10 vertebral joint, and the seat properties are included. All the mechanical properties of the proposed model are determined by fitting the test data listed in Tables 1 and 2. This proposed model is subsequently compared with Cho's original model by STH transmissibility, as listed in

Table 4. 9-DOF multibody model developed by Cho and Yoon[28)]

Inertial parameters				Geometrical parameters*3 (x, z), (mm)			
Mass (kg)		Inertia (kg·m^2)		C.G. location	Connection	Contact	Others
m_1	15.3 ± 2.5	I_1	0.90 ± 0.20	G_1 (212.5, –13.5)	J_1 (0, 0)	C_1 (88, –125)	Q_1 (–36, 475)*2
m_2	36.0 ± 6.0	I_2	1.10 ± 0.25	G_2 (–67.5, 192.5)	J_2 (–135, 385)	C_2 (240, 125)	Q_2 (425, –27)*1
m_3	5.5 ± 0.9	I_3	0.03 ± 0.00	G_3 (–138.5, 516)	–	C_3 (–120, 100)	Q_3 (–142, 647)*1
Biomechanical properties							
Translational				Rotational			
Stiffness (kN/m)		Damping (Ns/m)		Stiffness (Nm/rad)		Damping (Nms/rad)	
k_{v1}	36.0 ± 12.7	c_{v1}	14.7 ± 7.2	k_{R1}	0.0 ± 0.0	c_{R1}	2,576.5 ± 1,006.4
k_{v2}	36.0 ± 12.7	c_{v2}	14.7 ± 7.2	k_{R2}	100.0 ± 0.0	c_{R2}	1.3 ± 1.7
k_{v3}	2.3 ± 0.8	c_{v3}	0.4 ± 0.8				
k_{h1}	23.15 ± 5.45	c_{h1}	223.5 ± 167.1				
k_{h2}	23.15 ± 5.45	c_{h2}	223.5 ± 167.1				
k_{h3}	20.2 ± 7.1	c_{h3}	446.0 ± 165.4				
k_1	17.2 ± 4.6	c_1	380.6 ± 77.5				
k_2	25.0± 8.4	c_2	182.1 ± 40.1				
Seat properties							
Stiffness (N/m)				Damping (Ns/m)			
k_{sv1}	36,150	k_{sh1}	110,650	c_{sv1}	178.5	c_{sh1}	308.0
k_{sv2}	36,150	k_{sh2}	110,650	c_{sv2}	178.5	c_{sh2}	308.0
k_{sv3}	58,200	k_{sh3}	213,200	c_{sv3}	412.0	c_{sh3}	672.0

- 9-DOF system;
- 2-D model in sagittal plane;
- Developed to evaluate vehicle ride quality with backrest support;
- Modeled by 3 rigid segments interconnected by bushing elements (translational and rotational springs and dampers);
- Each mass is restricted to fore-and-aft, vertical, and rotational motions, and has 3 DOFs;
- Mechanical properties were obtained from a sitting posture with backrest only;
- Three vertical and horizontal spring-damper units representing the mechanical properties of seat and backrest cushions are serially connected to those under m_1 and m_2.
- Backrest support augments vibration transmissibilities of seated body and primary resonance frequency;
- Mass and inertial properties are the mean values[28)];
- *1: end point;
  *2: location used to calculate transmissibility;
  *3: coordinates for seated human body at a 21°-backrest posture.

Table 2.

The derivation of EOMs for the MB models in Tables 4 and 5 is very straightforward by applying the Newtonian or Lagrangian approaches. The advantages of the Lagrangian approach includes a lack of the need to draw free-body diagrams and complicated vector operations. However, the joint/reaction forces cannot be unveiled. In the following analysis, the proposed model is selected as the example. It should be noted that the following analysis is for the case with an inclined backrest and seat properties. For a normal sitting posture with or without a rigid seat, the changes are simple by correcting the inputs for geometric coordination and/or omitting the seat- and back-support properties.

It is worth mentioning that the springs and dampers between the seat cushion and the pelvis and the back cushion and the back are serially connected with the neglected cushion masses. To simplify the problem, one equivalent spring-damper unit (k_{eq} and c_{eq}) to replace the serial combination can probably be considered, as shown in Fig. 2. To solve the problem, it is first necessary to consider the original system in Fig. 2(a) as a 2-DOF system before deriving the EOMs. Since the mass of the seat cushion is neglected, the spring-and-damping force in the Laplace domain can be obtained as follows:

$$\frac{(k_1 + sc_1)(k_{s1} + sc_{s1})}{(k_1 + k_{s1}) + s(c_1 + c_{s1})}(Z_0 - Z_1) = (c_{eq}s + k_{eq})(Z_0 - Z_1)$$

Table 5. 14-DOF multibody model proposed in this study

Inertial parameters				Geometrical parameters*1 (x, z), (mm)		
Mass (kg)		Inertia (kg·m²)		C.G. location	Connection	Contact
m_1	20.3	I_1	1.160	G_1 (133, 70)	J_1 (329, 52)	C_1 (133, 0)
m_2	11.0	I_2	0.680	G_2 (–23, 97)	J_2 (–17, 84)	C_2 (–19, 0.0)
m_3	19.87	I_3	1.530	G_3 (–28.6, 474)	J_3 (–84, 139)	C_3 (–57, 386)
m_4	7.25	I_4	0.402	G_4 (18.1, 726)	J_4 (–8, 626)	–
m_5	12.9	–		G_5 (–27, 237)	–	–

Biomechanical properties

Translational								Rotational			
Stiffness (N/m)				Damping (Ns/m)				Stiffness (Nm/rad)		Damping (Nms/rad)	
k_1	72,000	k_{v1}	16,710	c_1	14.0	c_{v1}	8,010.0	k_{R1}	22.0	c_{R1}	104.0
k_2	2,300	k_{v2}	151,625*2 212,275*3	c_2	61.0	c_{v2}	47.0	k_{R2}	162.0	c_{R2}	30.0
								k_{R3}	328.0	c_{R3}	724.0
k_3	46,300	k_{h1}	614	c_3	1,500.0	c_{h1}	14.0	k_{R4}	915.0	c_{R4}	34.0
k_4	20,200	k_{h2}	905	c_4	266.0	c_{h2}	15.0				
k_{h3}	17,200	k_{v3}	2,300	c_{h3}	334.5	c_{v3}	154.0				
k_{h5}	25,000	k_{v5}	18,370	c_{h4}	266.0	c_{v5}	0.4				

- 14-DOF system, modified from model developed by Kim *et al.*[31] by matching measured data[15, 28, 33];
- 2-D model in sagittal plane;
- Modeled by 5 rigid segments coupled by bushing elements (translational and rotational springs and dampers), except viscera which connects to pelvis and torso by vertical and horizontal spring-damper units, respectively;
- Each segment has 3 DOFs, except viscera with only 2 DOFs;
- Thigh and pelvis were assumed to contact seat surface by vertical and horizontal spring-damper units to characterize buttocks tissue;
- Backrest angle α is 21° and 12° when compared with measured data[28, 33], respectively;
- *1: coordinates for seated human body at erect seated posture;
  *2: value for normal sitting posture without backrest support;
  *3: value for sitting posture with vertical or inclined backrest.

$$c_{eq} = \frac{c_1 c_{s1}}{c_1 + c_{s1}};\; k_{eq} = \frac{(c_1^2 k_{s1} + c_{s1}^2 k_1)s + k_1 k_{s1}(c_1 + c_{s1})}{(k_1 + k_{s1}) + s\,(c_1 + c_{s1})} \qquad (1)$$

where Z_0 and Z_1 are the Laplace transformation amplitudes of input excitation and vertical displacement of m_1, respectively; s is the Laplace operator; k_1, k_{s1}, c_1 and c_{s1} are the spring constant and damping coefficients of the body and seat masses, respectively. It should be noted that the equivalent spring constant k_{eq} is a function of s and is not a constant. Since the vibration responses were evaluated in frequency domain as mentioned previously, the Laplace operator s is replaced by $j\omega$ in the simulation, where j is squire root of -1 and ω is excitation frequency. The preceding equation is applied in the representations of equivalent (horizontal and vertical) properties of the human-seat interface.

As previously mentioned, the proposed model has 14 DOFs, hence 14 governing EOMs. The derivation of system EOMs is a complicated but straightforward procedure. In this research, both the Lagrangian and the Newtonian approaches are used to obtain the EOMs and mutually verify the analysis. Although the model is nonlinear, in a study of biodynamic responses for seated bodies the problems can be discussed in a linear range. Therefore, the aforementioned equations are then linearized by taking the Taylor series expansion at the static equilibrium positions with respect to the design variables, being the motions of the mass center (x_i, z_i, θ_i). The governing EOMs for the proposed model can be expressed in the following matrix form:

$$[M]\cdot\{\ddot{q}\} + [C]\cdot\{\dot{q}\} + [K]\cdot\{q\} = \{f_{\mathrm{E}}\} \qquad (2)$$

where $[M]$, $[C]$, and $[K]$ are the 14×14 mass, damping and stiffness matrices, respectively; $\{q\}$ is the vector of generalized coordinates; $\{f_{\mathrm{E}}\}$ is the force vector due to external excitation.

Methods for solving EOMs

Two solution techniques are generally implemented to resolve the dynamical problems. Since the response func-

Table 6. Research constructions for the modeling of a seated human body exposed to vertical vibrations in various automotive postures

Model Descriptions	Experimental Descriptions
• Cho's model ➢ Developed by Cho and Yoon in 2001[28] (Int J Ind Ergonomics **27**, 331–45); ➢ 2-D seated model with backrest support; ➢ 9-DOF linear system; ➢ Schematic and model parameters are listed in Fig. 1(a) and Table 4; ➢ Modified to the model without backrest support in comparison with proposed model; • Kim's model ➢ Developed by Kim *et al*. in 2006[31] (Int J Ind Ergonomics **35**, 817–29); ➢ 14-DOF nonlinear system; ➢ 2-D seated model without backrest support; ➢ Basis of proposed model in this study; • Proposed model ➢ Modified form Kim's model, by first fitting test data in *Table 1* for the case without a backrest, and subsequently by fitting the data in *Table 2* for the case with a backrest inclined 21°; ➢ 14-DOF linear system; ➢ Schematic and model parameters are listed in Fig. 1(b) and Table 5; ➢ 2-D seated model both with and without backrest support; ➢ Validated by test data in *Table 3*.	• Table 1 ➢ Synthesized on various measurements of erect seated humans without backrest support by Boileau and Wu in 1998[15] (J Sound Vib **215**, 841–62); ➢ Body masses limited to 49–94 kg; ➢ Constrained to vertical vibration excitations, excitation amplitudes were below 5 m/s^2, and specified as either sinusoidal or random; ➢ Excitation frequency range limited to 0.5–20 Hz; ➢ Used first to determine mechanical properties without backrest support for proposed model; • Table 2 ➢ Measurements on 10 subjects with backrest support by Cho and Yoon in 2001[28] (Int J Ind Ergonomics **27**, 331–45); ➢ Average mass of 61.1 kg; ➢ Backrest angle inclined 21°; ➢ Used to decide the mechanical properties with backrest support for Cho's model; ➢ Used secondly to decide mechanical properties with backrest support of proposed model; • Table 3 ➢ Measurements on 27 subjects with and without backrest support by Wang *et al*. in 2004[33] (Int J Ind Ergonomics **34**, 289–306); ➢ Average mass of 70.8 kg; ➢ No backrest, and backrest angles inclined 0° and 12°, respectively; ➢ Selected to validate proposed model.

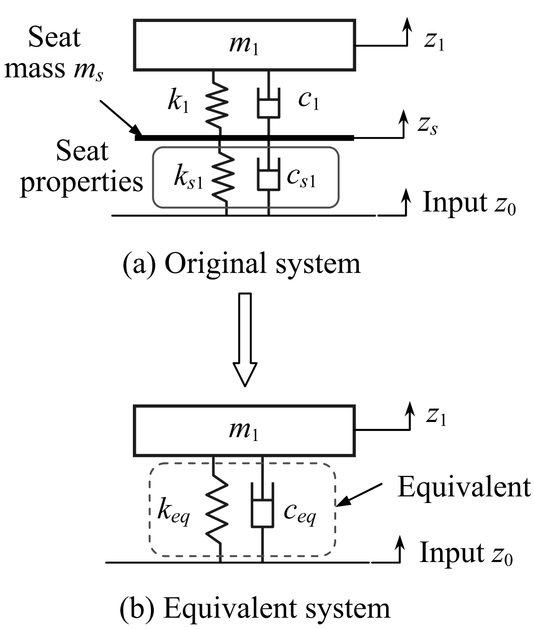


Fig. 2. Schematic of body-seat system and equivalent 1-DOF system.

tions from the experiments were processed in frequency ranges, as listed in Tables 1 to 3, each model in this study is simulated in a frequency domain for simplicity; hence, the corresponding solution technique is called the frequency-domain (FD) method. However, since nonlinear systems can be predicted only in a time domain, a further operation is needed to compare experimental results in a frequency range. Since all the models presented in this research are linear, the FD method is used.

The FD method is primarily suitable for linear systems with harmonic input excitation. The solution of this method takes account of only the steady-state response of the system. For example, by performing the Fourier transformation on equation (2), the following matrix form of the equation can be obtained:

$$\{Q(j\omega)\} = \left[[K] - \omega^2[M] - j\omega[C]\right]^{-1} \cdot \{F_E(j\omega)\} \qquad (3)$$

where $\{Q(j\omega)\}$ and $\{F_E(j\omega)\}$ are the complex Fourier transformation vectors of $\{q\}$ and $\{f_E\}$, respectively, in equation (2), and ω is the excitation frequency. Vector $\{Q(j\omega)\}$ contains complex displacement responses from the 14 mass segments as a function of ω. On the basis of the preceding discussion, the STH transmissibility and AP mass can be obtained.

Biodynamic Responses of Seated Body

From the foregoing discussions, it is obvious that the

Table 7. Mode shape of proposed model at primary resonance frequency of 5.67 Hz

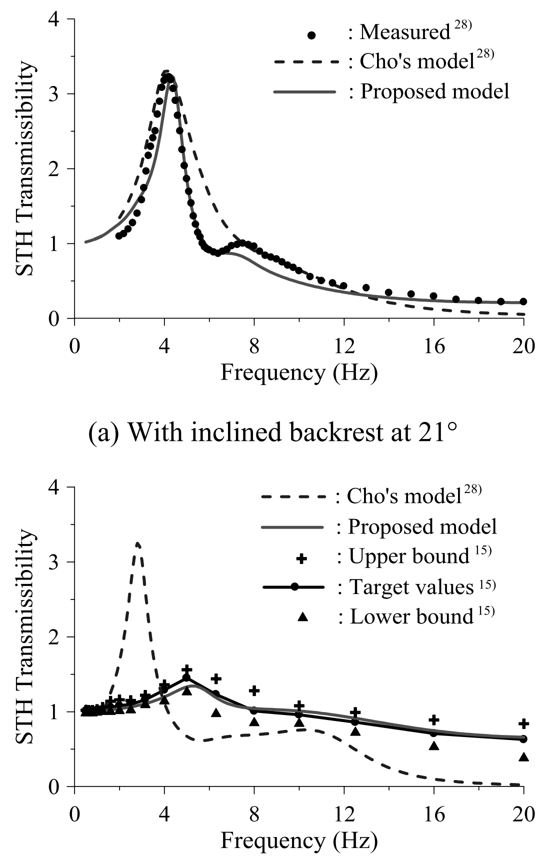
Motion	Thigh m_1	Pelvis m_2	Torso m_3	Head m_4	Viscera m_5
Horizontal motion x_i, m	–0.22626	–0.01415	–0.00289	–0.01147	–0.01393
Vertical motion z_i, m	0.06175	–0.00081	0.01349	0.17748	0.45263
Pitch motion, θ_i, radian	-4.86×10^{-5}	–0.00595	0.02758	0.00964	–

MB model is one of the most popular analytical methods for the study of biodynamic responses of seated human bodies. Moreover, for the responses of a seated body exposed to vertical vibrations, the mathematical models of the mechanisms must be at least 2-D in the sagittal plane. Through the years, many data have been generated by different investigators to characterize these response functions by using widely varying experimental conditions. Those data have more appropriately been summarized by using the simulation of the mathematical models listed in this study, under a well-defined range of assumptions. As indicated in the review of the literature, some MB models have been established with various degrees of complexity, depending on the analytical objectives. Among these, two suitably selected MB models with adequate information and complication were discussed in detail and systematically analyzed. These two models are capable of being modified to satisfy the conditions of a seated body in different postures in automotive environments, having been both assessed and validated with measured data in the published literature. Finally, the model best fitted to the experimental data is recommended.

Validation of mathematical models

Studies on the responses of a normal (erect) seated human body exposed to vertical vibrations exhibit a consistent pattern, in which a principal peak, or resonance, in frequency response functions occurs at about 5 Hz. Hence, the modal analysis is first implemented for the proposed model of such a seated body without backrest support. The principal resonance occurs at a frequency of 5.67 Hz; whereas, the result from the literature[18, 29, 34] is 5.66 Hz. The damped natural frequency of the corresponding mode is around 5.2 Hz from the calculated STH transmissibility and AP mass values. This mode consists of an entire body mode, in which the head, spinal column, and the pelvis move almost rigidly, with vertical deformation of the buttocks tissue and head motion in phase with a vertical motion of viscera. The corresponding mode shape is listed in Table 7.

Next, the proposed model is adjusted to a sitting posture shaped by a backrest inclined 21°, the same angle as in the original model developed by Cho and Yoon[28]. The simulation results for STH transmissibility are shown in



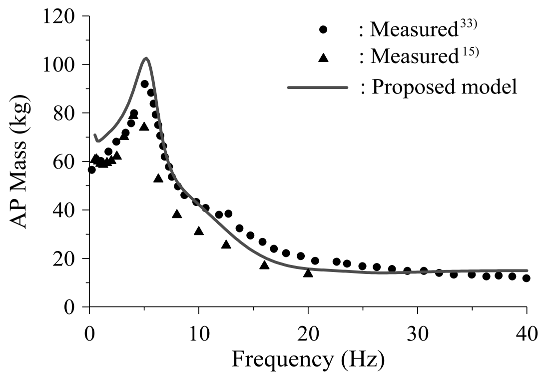
(a) With inclined backrest at 21°

(b) Normal posture without backrest support

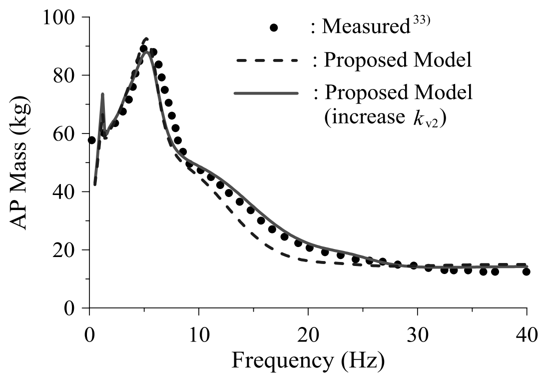
Fig. 3. Comparisons of STH transmissibility at various sitting postures.

Fig. 3(a). Both models seem to provide very good representation in comparison with the measured data. Fig. 3(b) shows the comparison when Cho's model is adjusted to a normal posture without a backrest and seat properties. The proposed model still provides a very good approximation to the target values of the experimental data; however, the result from Cho's model is far from what was expected, probably because the original modeling situations were devised to fit the individual measurements only for the case with a backrest support.

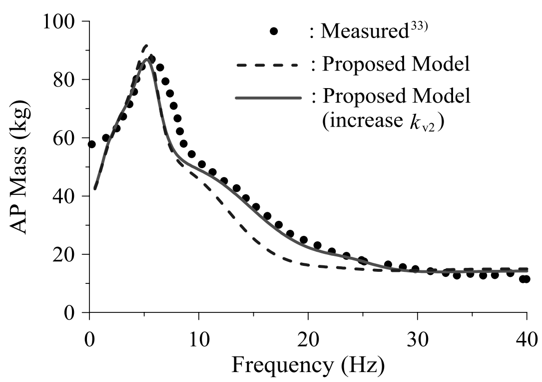
In addition, further simulation is conducted for the proposed model to assess the AP mass in a normal sitting posture, as shown in Fig. 4(a). It is noted that the simulations seem to fit one measured data set[33] better than the other[15], perhaps as a result of the sampling method



(a) Normal posture without backrest support



(b) With vertical backrest



(c) With inclined backrest at 12°

Fig. 4. Comparisons of AP mass at various sitting postures.

used. The former data set[33] has a mean mass of 70.8 kg, which is very close to the model mass of 71.32 kg. Although the latter set[15] reported a mean mass close to 70 kg, it was collected from a wide range of measurements under different testing conditions. The body mass influences the AP mass values of a seated body, a topic worthy of further discussion in detail. The proposed model is further adjusted to sitting postures with vertical and inclined (12°) backrests, for which the evaluated values of the AP mass appear as curves in Figs. 4(b) and (c). The simulations all provided very good agreement with the measured data. However, the results also indicated that an increase in the stiffness value of the pelvis (k_{v2}) tends to increase the accuracy in prediction. This phenomenon might be attributed to the decrease of muscle tension by the backrest[28], thereby increasing pelvic stiffness.

Conclusion and Recommendations for Future Study

A study of MB models of a seated human body exposed to vertical vibrations has been implemented. The model proposed in this research has been analyzed and validated in terms of STH transmissibility and AP mass by various experimental data from the published literature. The proposed model has been further compared with similar model in the literature on automotive sitting environments. From the analysis and validation, the following comments can be made:

1. For responses of a seated body exposed to vertical vibrations, the models must be at least 2-D in the sagittal plane. Therefore, the MB models in this study were observed when sitting both with and without backrest supports, irrespective of hand positions, while the feet were supported and allowed to vibrate. In the biodynamic analyses both models were simplified to linear systems to reduce the analytical and simulational complexities.
2. From the modal analysis and validations on two biodynamic response functions of STH transmissibility and AP mass, the proposed model has proven to fit the experimental data in different automotive sitting environments very well. It is recommended that the proposed model be used in evaluations of the biodynamic responses of a seated human body exposed to vertical vibrations in various automotive postures.
3. It is believed that this research has provided a more comprehensive understanding of the aforementioned biodynamic responses. Future research may be extended to the following.
   (1) The mass of a seated body has considerable influence on certain biodynamic response functions. Therefore, further research can be conducted on the influences of different mass values.
   (2) The seated model proposed in this research approximates passenger-like postures regardless of the position of the hands. Since certain vibrations may transmitted through the hands, such as from the steering wheel, it may be worthwhile to investigate the influence of hand positions on the biodynamic response functions or the modeling of the driver-like postures.

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