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Effect of Low-Frequency Vibration on Human Body in Standing Position Exposed to Railway Vehicle

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ABSTRACT:

In this paper, the dynamic characteristics of the human body were investigated by developing a 3-D finite element model based on 50th percentile anthropometric data for a 54 kg Indian male subject in standing position by considering human body segments as an ellipsoid. The finite element modal analysis is carried out to extract several low-frequency vibration modes and its vibration mode shapes were presented in this paper. The results show that the lowest natural frequency of the standing passenger model occurs in the fore-and-aft direction. The second natural frequency occurs in the lateral direction and the first order natural frequency of the standing passenger model in the vertical direction occurs at 5.379 Hz. The model will be helpful to predict the vibration response of human body under various vibration environment encounters in the railway vehicle.

KEYWORDS:

Railway vehicle; Modal Analysis; Human Vibration; Standing Position; Finite Element Method

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NOMENCLATURE:

$[M]$	Mass matrix
$[K]$	Stiffness matrix
$\{\emptyset\}_i$	Eigenvector of i^{th} mode
γ_i	Participation factors of i^{th} mode
$\{D\}$	Assumed unit displacement vector in each global cartesian directions and rotation about each axes.
$M_{eff,i}$	Effective mass of i^{th} mode.

1. Introduction

Across the world train travel is considered to be the cheapest, safest, comfortable and most convenient mode of transportation. In India, a large number of people whether it be office goers or students, prefer local trains to commute to their destination. During peak hours local trains operate at higher speeds and shorter interval to reduce overcrowding which may lead to frequent acceleration and deceleration. Also due to irregularity in the track geometry, vibrations are induced in the railway vehicle [1-2]. These vibrations are transmitted to human body from floor, seat, hand-rest, and backrest. In such cases, humans are exposed to whole-body vibration. Frequent exposure to whole-body vibrations for a long duration may cause fatigue, pain, and discomfort at body joints and other parts of the body. To protect commuters from psychologically, physiological discomfort and musculoskeletal disorders, it necessitates the design of vibration attenuating railway vehicle [3-4]. The humans are more sensitive to low-frequency vibration (0.1 to 20 Hz) and even small doses can create discomfort [5]. The performance of passenger in various postures to execute activities such as reading, writing, and working on laptops etc. degrades, even due to small irregularities on rail tracks [6].

The vibration magnitude has little effect on frequency dependence human discomfort [7]. Ismail et al [8], studied the effect of a whole-body vibration exposure on train passengers to determine daily vibration exposure and vibration dose value. They concluded that with the increase in vibration exposure duration and total trips passed by the passengers, vibration absorption by human body further enhances. Bhiwapurkar et al [9], studied the effect of random vibrations in mono, dual and multi-axis in the low-frequency range on writing task on a laboratory simulator of the railway vehicle. Dual and multi-axis vibration resulted in more difficulty, while in mono axes performance degradation was observed only in vertical and lateral direction. Experimental and field study techniques require extensive and rigorous data analysis and are time-consuming too [10].

In biomechanics, finite element method has been used frequently for studying the dynamic behaviour of mechanical structures. Kitazaki et al [19] used beam, spring and mass elements for analysing the spine, viscera, head, pelvis and buttock tissue in the mid-sagittal plane and found the resonance frequency at 5 Hz. A 3-D FE model of the human spine T12-Pelvis segment was developed by Guo et al [20], to extract resonance frequency and mode shapes. The resonance frequency of the model in the vertical direction is found at 7.21 Hz. Liu et al [21] developed a three-dimensional FE model of the seated human body with the torso and skeletal structures (pelvis and femurs) represented as rigid parts and soft tissues of buttocks and thighs are represented as deformable parts to assist seat design by representing dynamic human-seat interaction. The model exhibited three modes of vibration at frequencies less than 15Hz viz. 1.7, 6.2, and 13 Hz. A two-dimensional FE model of the human hand-arm system was developed to estimate modal frequencies and these frequencies are then compared with experimental results to update the mechanical properties of the model [22]. Pionteck et al [23], used Operational Modal Analysis to update modal parameter of 2D FE model of the lower limb. The objective of present study is to develop FE model of human body represented by ellipsoidal segment with homogeneous material properties and to employ this model to determine the resonant frequencies of a standing passenger in a railway vehicle.

2. Modelling and analysis

To study the dynamic behavior of human body in standing position a 3D CAD model was developed in Solidworks and subsequent analysis was performed in Ansys Workbench. A 3-D finite element model based on 50th percentile anthropometric data for a standing 54- kg Indian male subject has been developed. The 3D model consists of 15 body segments: head, neck, upper torso, central torso, lower torso, upper and lower arm (left and right), upper and lower leg (left and right), and foot (left and right). Each body segment is considered as of ellipsoidal shape [15]. These solid ellipsoidal models define the volume of the segment they represent and hence the mass of each part. The model is developed with five percent truncated ellipsoidal segments using anthropometric data from Chakrabarti [24]. The dimensions of semi-axes of each truncated ellipsoidal segment as computed from formulae in Nigam and Malik [15] are shown in Table 1.

Table 1: Specifications of body segments [15], [24-25]

Body segment	a (mm)	b (mm)	c (mm)	Mass (kg)	E_G ratio
Head	73.50	73.50	93.50	2.3233	0.104
Neck	53.64	53.64	40.00	0.52935	0.409
Upper Torso	149.00	107.00	78.00	5.7507	1.072
Central Torso	129.50	96.00	138.75	7.9853	0.014
Lower Torso	165.50	145.50	105.75	15.073	2.407
Upper Arm	38.83	38.83	156.00	1.0844	0.518
Lower Arm	36.29	36.29	122.00	0.73606	0.102
Upper Leg	67.48	67.48	275.00	5.7607	4.131
Lower Leg	50.77	50.77	229.00	2.7149	9.990
Foot	47.00	124.00	30.50	0.87356	0.143

The material property of different ellipsoidal body segment is assumed as linear elastic and isotropic. Although mass in the human body is not distributed homogeneously, average densities of different body segments are nearly same [14]. Therefore, the density of each segment is taken same and equal to 1195.89 kg/m^3, the average density of whole body [15]. A human body is composed of a number of constituents such as bones, muscles/tissues, organs, and fat. The mechanical properties of these constitutes vary in different body segment. Since considering properties of each constituent would require a proper proportion of each, therefore the deformation in the body is assumed to be contributed by bones (E_b) and tissues (E_t) [15]. Further, the elastic moduli for the bony parts like legs, limbs, and upper and lower torso would be higher than for the fleshy parts like central torso, neck, and feet [18]. Therefore, Young's modulus of each ellipsoid body segment is taken as a fraction of the geometric mean of the elastic modulus of bone and tissue as obtained by Gupta and Gupta [18]. Poisson's ratio was taken as 0.3 based on an experimental study of Mukherjee et al [26].

The contact between different body segments is considered as bonded thus allowing no relative motion at the interface. No separation contact condition is chosen between the lower arm and lower torso. The bottom face of feet is considered as attached to the floor of a railway vehicle and constrained in all directions and hence fixed boundary condition is applied to them. The model is meshed into finite elements using hexahedral elements keeping mid-side node as program controlled. The mesh sensitivity test was carried with different element size to obtain optimized mesh. The final model consists of 185645 nodes and 82284 elements. The modal analysis was performed to determine the natural frequencies and mode shapes. The natural frequencies were calculated up to the frequency limit of 120 Hz in order to incorporate entire range of exciting frequencies that may be encountered on the floor of the railway vehicle. The frequencies and associated mode shapes were obtained by solving a linear equation of motion for free un-damped vibration:

$$[M]\{\ddot{x}\} + [K]\{x\} = \{0\} \quad (1)$$

3. Results and discussions

After modal analysis, natural frequency and vibration modes of the standing human body model were obtained. A 3D continuous structure has infinite degrees of freedom and hence it has infinite numbers of natural frequencies and associated modes. In order to explore the full range of excitation frequency, first 100th resonance frequencies were extracted. To identify modes that will contribute to excitation in a particular direction, effective mass participation factor (EMPF) were calculated. The participation factors are given by:

$$\gamma_i = \{\emptyset\}_i^T\, [M]\{D\} \quad (2)$$

The effective mass is obtained by:

$$M_{eff,i} = \frac{\gamma_i^2}{\{\emptyset\}_i^T [M]\{\emptyset\}_i} = \gamma_i^2,\ if\ \{\emptyset\}_i^T [M]\{\emptyset\}_i = 1 \quad (3)$$

The EMPF provides a proportion of the energy contained within each resonant mode since it indicates the amount of system mass participating in a particular mode. A mode with a large effective mass is usually a significant contributor to the response of the system.

Fig. 1 represents first 100th resonant frequencies and their respective effective mass participation factors in linear directions. Out of 100 resonance frequency modes, only a few modes show significant EMPF. In most of the modes the energy content is so low that even if the exciting frequency is close to one of the natural frequency, no appreciable resonance effect would be witnessed. Hence, in the present study to any mode that contributes more than 1 % of total mass is identified as a probable mode of the resonant frequency. Table 2 shows the resonance frequencies that have a significant impact on human body response to excitation. The response of the human body to single, dual or multi-axis excitation is always coupled with rotational motion about an axis. Fig. 2 represents first 100th resonant frequencies and their respective effective mass participation factors in rotational directions. Many resonance frequency modes show a significant value of EMPF, especially in a low-frequency range. Similar criterion (EMPF>=1 %) was considered to identify prominent resonant modes and shown in Table 2.

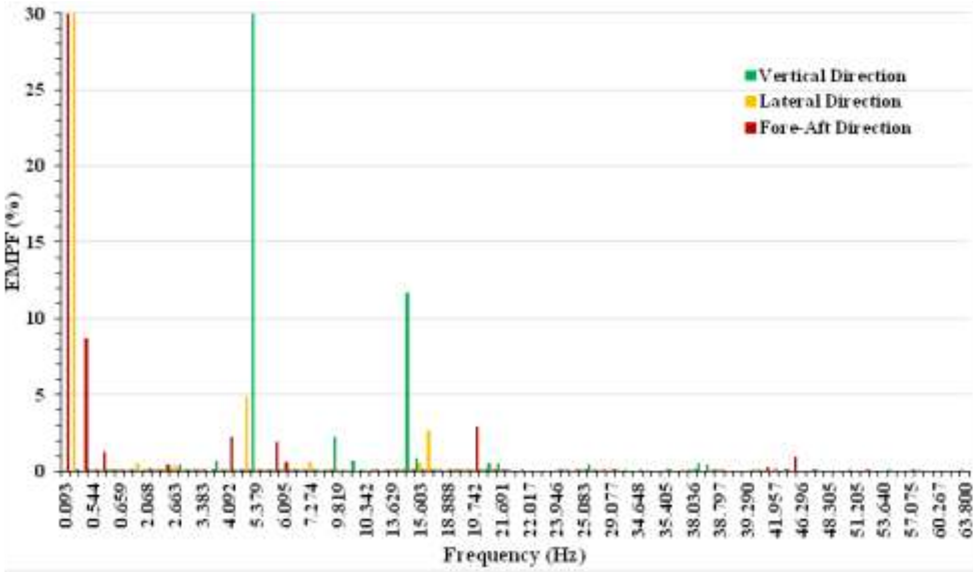

Fig. 1: First 100th resonant frequencies and their respective effective mass participation factors in linear directions

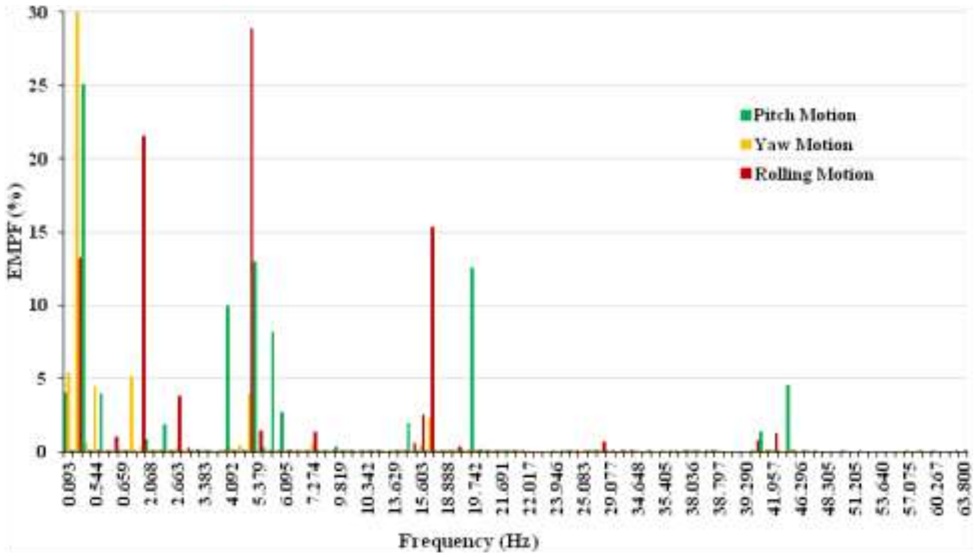

Fig. 2: First 100th resonant frequencies and their respective effective mass participation factors in rotational directions

Table 2: Prominent resonance frequency of human body in standing position

Vertical		Lateral		Fore-and-aft		Pitch		Yawing		Rolling	
Mode	Value (Hz)	Mode	Value (Hz)	Mode	Value (Hz)	Mode	Value (Hz)	Mode	Value (Hz)	Mode	Value (Hz)
22	5.379	2	0.155	1	0.093	1	0.093	1	0.093	2	0.155
31	9.818	21	4.445	3	0.462	3	0.462	2	0.155	6	0.652
39	15.268	41	16.683	5	0.631	5	0.631	4	0.543	9	0.972
-	-	-	-	19	4.092	12	2.532	8	0.957	13	2.662
-	-	-	-	24	5.861	19	4.092	21	4.445	21	4.445
-	-	-	-	46	19.741	22	5.379	41	16.683	22	5.379
-	-	-	-	-	-	24	5.861	-	-	28	7.274
-	-	-	-	-	-	25	6.095	-	-	40	15.603
-	-	-	-	-	-	39	15.268	-	-	41	16.683
-	-	-	-	-	-	46	19.741	-	-	79	41.956
-	-	-	-	-	-	78	41.648	-	-	-	-
-	-	-	-	-	-	81	42.560	-	-	-	-

The low-order excitation frequencies in the range of 0.5-20 Hz have a greater impact on human comfort. Analyses of mode shape (Fig. 3) and Table 2 show several flexural natural frequencies < 20 Hz, but the lowest vertical frequency is ~ 5 Hz. The natural frequency obtained may be broadly divided into three ranges: 0.1-3 Hz, 4-7 Hz, and 9-20 Hz. The first range has the dominant effect of fore-and-aft motion along with pitch, yawing and rolling motion. The first mode at 0.09 Hz and the second mode at 0.155 Hz result in fore-and-aft and lateral motion respectively of the whole body with respect to foot and it corresponds to the first mode of the beam with one end fixed. At 0.4627 Hz the upper body and at 0.6311 Hz only the lower arms have motion in a fore-and-aft direction. The head and lower arms are most affected body segment under this range.

In the second range, at 4.092 and 4.445 Hz upper and lower body moves out of phase in a fore-and-aft and lateral direction respectively with respect to the lower torso. It corresponds to the fourth mode of the fixed-free beam. At 5.379 Hz entire body have an axial deformation in phase. A significant pitch motion is also observed in this range. In the third range, opposite phase motion of upper and lower body in the vertical direction was observed at 15.2683 Hz. The rolling and pitching motion of lower legs and feet were observed at 16.684 and 19.741 Hz respectively. Previous studies show that for standing person main resonance frequency occur around 5.5 Hz and second resonance frequency occur in the range of 9-14 Hz. The resonant frequency obtained in the present study lies within the range as in the published literature.

From the modal analysis, it is observed that resonant frequency of human body in standing position lies in the range of low-frequency vibration. Standing passengers in a railway vehicle are exposed to external excitation from the floor, support or handrail etc. This excitation energy may enter into the body through various contact regions and amplifies when its frequency matches with the natural frequency of the human body. The occurrence of such resonance condition causes imbalance and postural instability. The transmission of excessive vibratory energy through the body may cause a sensation of pain in spine, knee joints and in other parts of the body. Also, human performance degrades in such vibratory environment to perform activities which involves head and lower arms such as operating electronic devices (e.g. smart phones, feature phones, iPods), reading, writing, drinking, eating etc. The FE model developed in the study appeared capable of representing the resonant frequency of the human body. The model may further be employed to study the biodynamic response of human body under different excitation level. A linear material property has been used to represent human body but to acquire more realistic response a non-linear material property may be employed.

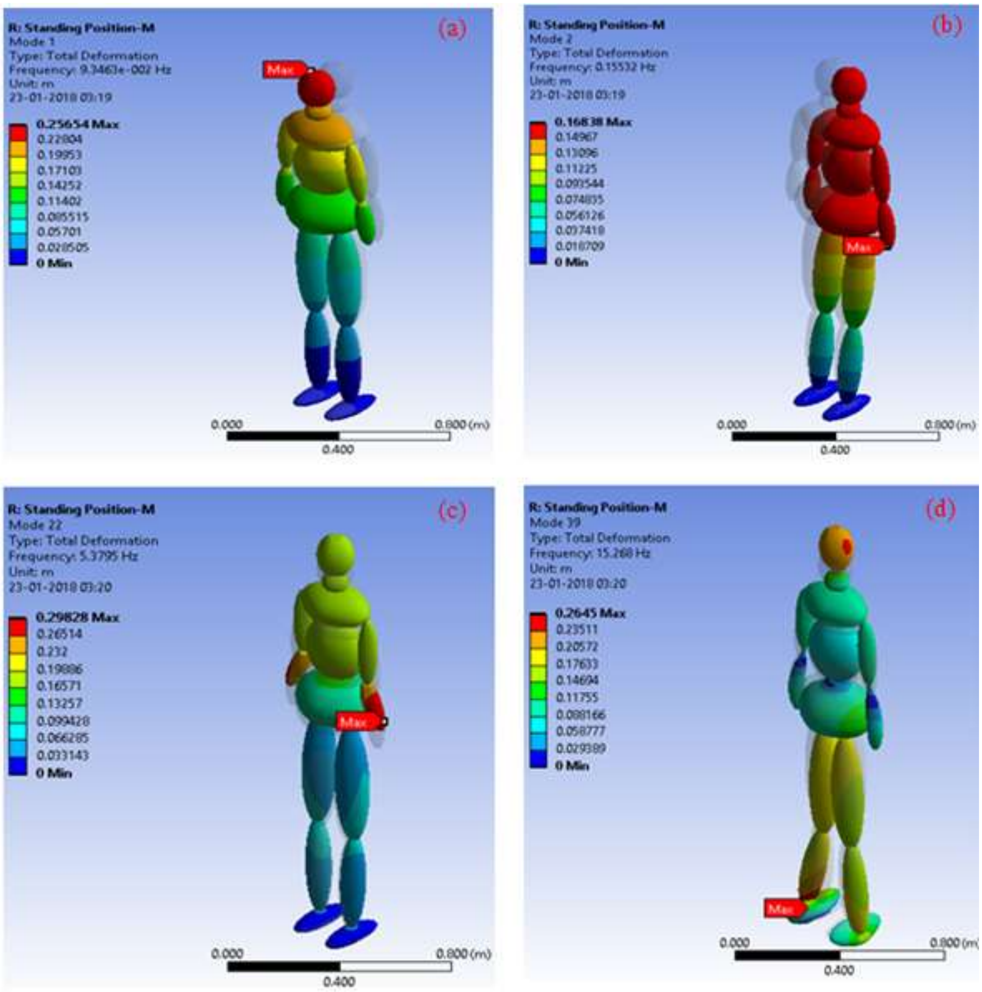

Fig. 3: Vibration modes of the model of the standing human body model. (a) First mode in the fore-and-aft direction, 0.09 Hz, (b) First mode in the lateral direction, 0.155 Hz, (c) First mode in the vertical direction, 5.3795 Hz, (d) Second mode in the vertical direction, 15.268 Hz

4. Conclusions

A 3D FE model of the human body based on anthropometric data was developed and was used to extract the resonance frequencies and mode shapes of standing person. The lowest natural frequency of the model is in the fore-and-aft direction. The second order natural frequency is obtained in the lateral direction. The first order resonant frequency of human body in the vertical direction is obtained at 5.379 Hz. The study indicated that if the external excitation frequency due to the irregularity of vertical profile of track coincides with the natural frequency of a person standing on the floor of a railway vehicle, then pain, fatigue, and discomfort would be experienced at different body parts. Further, the model may be used to study the effect on the human body at different floor excitation level.

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