A CONTINUOUS MODEL FOR THE VERTICAL VIBRATION OF THE HUMAN BODY IN A STANDING POSITION

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ABSTRACT

This paper is concerned with modelling the vertical vibration of the human body in a standing position. The human body is modelled as a column consisted of two uniform members with different properties. Solutions of the free vibration of the model are given and the effect of several distributions of the stiffnesses are considered. The modal mass, frequencies and axial stiffnesses of four people are determined using a combination of this model and experimental experiments. Based on the proposed model, it is found that: 1) the fundamental mode of the human body shows that all parts of the human body vibrate in the same direction and the top of the body has the maximum movement; 2) the modal mass of the human body can be calculated and the model provides a theoretical basis for studying human-structure vibration.

1. INTRODUCTION

The study of the response of the human body to shock and vibration is an important part of biomechanics engineering research, and experimental and numerical investigations have been conducted for many years. Because the human body is a complex organic system, experimental investigations play an important role in studying human body vibration. A shaking table is often adopted for measuring the impedance or the apparent mass from which the fundamental frequency of the human whole-body can be abstracted. This technique seems unstable for people in a standing position, because people naturally stabilise themselves when the shaking table moves. The stabilisation may be tensing the muscle or bending the knees. The former will increase the body stiffness which results in a higher body frequency while the latter will reduce the whole body stiffness which produces a lower frequency. This may explain why the resonance frequencies of standing men vary over a wide range from 4 to 16 Hz[1]. A method for the indirect measurement of the human whole-body frequency has been developed[2] which can avoid the above difficulties in the measurement of the frequency at the standing position. However, it seems improbable that the higher frequencies and vibrating modes of a human body can be measured through experimental studies.

A viable alternative to experimental evaluation is to approximate the human body by a mathematical model and analyse the desired behaviour of the model. A human body can be represented by a lumped system consisting of masses, springs and dashpots. ISO5982 [3] and Ref[4] provided a two degree-of-freedom system, although it is really two single-degree-of-freedom systems, with the model parameters being determined by experiments. Nigam and Malik[5] introduced a 15 DOF spring mass system. This model was based on an anthropomorphic model of the average male body in a standing posture with the body modelled using ellipsoidal segments. Assumptions of the mass and stiffness of these segments were used to derive the lumped parameters of the system. In general the difficulty with using this type of model is to determine the parameters of the system, such as mass, stiffness of spring and damping of each lumped mass.

This paper treats a human body as a continuum rather than a discrete system. The vertical vibration of the human body in a standing position is modelled as the axial vibration of a one-dimensional member. To represent the main characteristics of the human body, the one-dimensional member consists of two uniform bars with different properties. In combination with the indirect

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measurement of the fundamental frequency of the human body at the standing position, the axial stiffness of the human body can be determined and the frequencies of higher modes can be predicted. The advantages of using this model are that the modal mass of the human body can be evaluated and the model has fewer unknowns to be determined than the discrete system.

2. ANALYSIS OF THE VIBRATORY MODEL

2.1 Assumptions for the model development

To study a human body theoretically, it is important to clarify the basic assumptions involved in the development of the model. They are:

1. *Local vibrations in a human body are neglected.*
For the global vibration of a human body, the local vibrations of the body, such as the arm vibration and eye ball vibration, are insignificant.

2. *The human body is modelled in two uniform parts.*
The human body is a complex continuum. It would be a hopeless task to attempt to model this complex system exactly. Basically, the human body consists of four main parts: head, torso, arms and legs (Fig.1.a). Because the head has less than 5% of the whole body weight[5] and the vibration of arms is neglected, the head, arms and the torso are grouped as the upper part of the body while legs and feet are grouped as the lower part (Fig.1.b). Only the differences in the mechanical properties between the two parts are modelled (Fig.1.c).

3. *The upper part has two third and the lower part has one third of the whole body weight.*
Nigam[5] gave the weight of fifteen segments of a whole body as 74.9kg with the body segments considered to be ellipsoidal and the density of each segment taken to be the same and equal to the average density of the whole body. When the weight of these segments are grouped into the upper and lower parts of the body, it is noted that the lower part has a weight of 24.94kg while the upper part is 49.96kg, i.e. almost the double the weight of the lower part.

4. *The upper and lower parts have the same height.*
By simple measurements, the heights of the upper and lower parts of people are approximately the same.

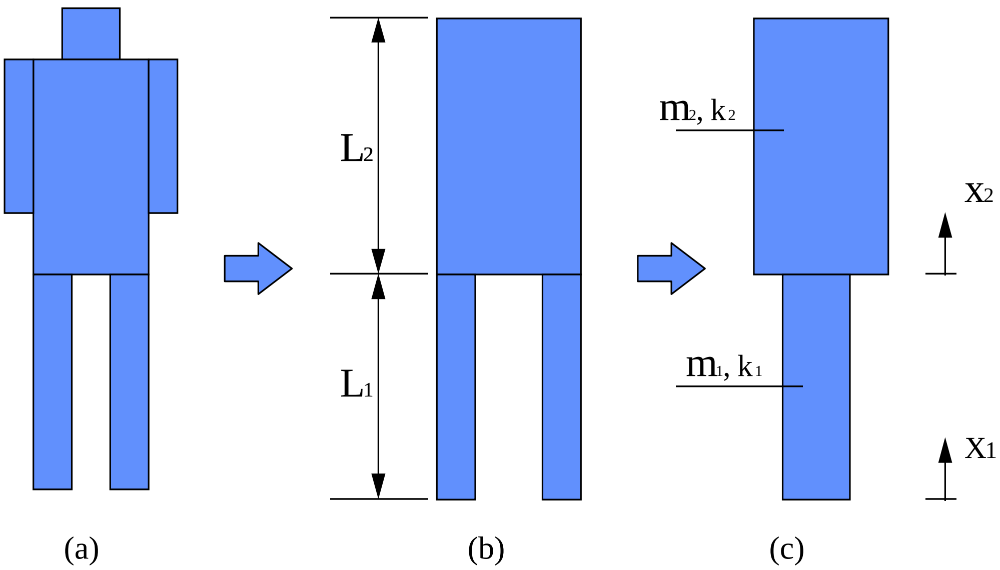


Fig.1 Model Simplification of a Standing Person

Based on the above assumptions, the vertical vibration of the human body can be studied as the axial vibration of a column assembled from two uniform bars having different properties.

2.2 Free axial vibration of the model

For a column represented by two uniform bars (Fig.1.c), the properties are constant along each segment and the equation of axial motion[6,7] is:

$$m_i \frac{\partial^2 u}{\partial t^2} - k_i \frac{\partial^2 u}{\partial x^2} = 0 \qquad i = 1,2 \qquad (1)$$

The solution of the above equation has the following form

$$u(x,t) = T(t)\Phi(x) \qquad (2)$$

By substituting Eq.2 into Eq.1 and separating the variables, the differential equation of the mode shape is

$$\Phi_i''(x) + b_i^2 \Phi_i(x) = 0 \qquad i = 1,2 \qquad (3)$$

in which

$$b_i = \omega \sqrt{\frac{m_i}{k_i}} \qquad i = 1,2 \qquad (4)$$

where m_i, k_i and $\Phi_i(x)$ are the mass density, the tension stiffness of the cross-section and the mode shape of the i th segment of the column. ω is the frequency of the column in the axial vibration. The solution of Eq.3 is

$$\Phi_i(x) = C_i \cos b_i x_i + D_i \sin b_i x_i \qquad i = 1,2 \qquad (5)$$

in which the coefficients C_i and D_i define the mode shape and can be determined according to the boundary conditions.

For the lower part: (*i=1*)

At $x_1 = 0$ $\quad \Phi_1(0) = 0$ (a)

At $x_1 = L_1$ $\quad N_1(L_1) = k_1 \Phi_1'(L_1)$ (b)

For the upper part: *(i=2)*

At $x_2 = 0$ $\quad \Phi_2(0) = C_2$ (c)

At $x_2 = 0$ $\quad N_2(0) = k_2 \Phi_2'(0)$ (d)

At $x_2 = L_2$ $\quad N_2(L_2) = k_2 \Phi_2'(L_2) = 0$ (e)

Due to continuity, the deformation and force at the transition point between the lower and upper parts are the same, i.e.

$$\Phi_1(L_1) = \Phi_2(0) \qquad \text{and} \qquad N_1(L_1) = N_2(0) \qquad (f)$$

Following Eqs.(*a-d* and *f*), the coefficients C_1, C_2, D_1 and D_2 can be determined and the modes become:

$$\Phi_1(x_1) = D \sin b_1 x_1 \qquad 0 \le x_1 \le L_1$$

$$\Phi_2(x_2) = D\{\sin b_1 L_1 \cos b_2 x_2 + \sqrt{\frac{m_1 k_1}{m_2 k_2}} \cos b_1 L_1 \sin b_2 x_2\} \qquad 0 \le x_2 \le L_2 \qquad (6)$$

Where D is an appropriate factor that makes $\Phi_2(L_2)=1$. Substituting the second formula of Eq.6 into Eq.(e) yields the transcendental axial frequency equation as follows:

$$\tan b_1L_1 \tan b_2L_2 = \sqrt{\frac{m_1k_1}{m_2k_2}} \qquad (7)$$

2.3 Solutions of special cases

When the ratio of the tension stiffnesses of the upper and lower parts of the column are given, the solution of Eq.7 can be obtained. However it is not clear what the stiffness ratio is. Several possible ratios are considered and the most appropriate one is found later from the comparison between calculations and measurements. Three cases are given as follows:

<u>Case 1</u>. If $k_1 = 2k_2$, then $b_2 = 2b_1$ and $\sqrt{\frac{m_1k_1}{m_2k_2}} = 1$

The frequency equation becomes

$$\tan b_1L_1 \tan 2b_1L_1 = 1 \qquad (8)$$

The first four solutions of Eq.8 are

$$b_1L_1 = 0.5236,\ 2.618,\ 3.665,\ 5.760$$

The corresponding mode shapes are

$$\begin{aligned}
\Phi_1(x_1) &= D\sin(b_1L_1\frac{x_1}{L_1}) && 0 \le x_1 \le L_1 \\
\Phi_2(x_2) &= D\sin[b_1L_1(1+\frac{2x_2}{L_2})\ ] && 0 \le x_2 \le L_2
\end{aligned} \qquad (9)$$

<u>Case 2.</u> If $k_1 = k_2$, then $b_2 = \sqrt{2}b_1$ and $\sqrt{\frac{m_1k_1}{m_2k_2}} = \frac{\sqrt{2}}{2}$.

The frequency equation is

$$\tan b_1L_1 \tan \sqrt{2}b_1L_1 = \frac{\sqrt{2}}{2} \qquad (10)$$

The first four solutions of the above equation are:

$$b_1L_1 = 0.5813,\ 2.0,\ 3.237,\ 4.553$$

The corresponding mode shapes are

$$\begin{aligned}
\Phi_1(x_1) &= D\sin(b_1L_1\frac{x_1}{L_1}) && 0 \le x_1 \le L_1 \\
\Phi_2(x_2) &= D\{\sin b_1L_1 \cos(\sqrt{2}b_1L_1\frac{x_2}{L_2}) + \frac{\sqrt{2}}{2}\cos b_1L_1 \sin(\sqrt{2}b_1L_1\frac{x_2}{L_2})\ \} && 0 \le x_2 \le L_2
\end{aligned} \qquad (11)$$

<u>Case 3.</u> When $2k_1 = k_2$, there are $b_2 = b_1$ and $\sqrt{\frac{m_1k_1}{m_2k_2}} = 0.5$.

The frequency equation is

$$\tan^2 b_1L_1 = 0.5 \qquad (12)$$

The first four solutions of the above equation are:

$$b_1L_1 = 0.6155,\ 2.526,\ 3.757,\ 5.668$$

The corresponding mode shapes are

$$\Phi_1(x_1) = D\sin(b_1L_1\frac{x_1}{L_1}) \qquad 0 \le x_1 \le L_1$$

$$\Phi_2(x_2) = D\{\sin b_1L_1 \cos(b_1L_1\frac{x_2}{L_2}) + 0.5\cos b_1L_1\sin(b_1L_1\frac{x_2}{L_2})\ \} \qquad 0 \le x_2 \le L_2 \tag{13}$$

3. MECHANICAL CHARACTERISTICS OF STANDING PEOPLE

3.1 Modal mass

When considering vibration of a particular mode, the modal mass is required for the analysis. The modal mass of the *j th* mode is

$$M_j^* = \int_0^{L_1} m_1\Phi_{j1}^2(x)dx + \int_0^{L_2} m_2\Phi_{j2}^2(x)dx \tag{14}$$

For the *j* th mode the mode shape is determined using the *j* th solution of b_1L_1. Following the assumptions that $L_1 = L_2$ and $m_2 = 2m_1$, for people having a total mass of M, the mass densities of the lower and upper parts of the column are respectively:

$$m_1 = \frac{M}{3L_1} \text{ and } m_2 = \frac{2M}{3L_1} \tag{15}$$

Substituting Eq.15 into Eq.14 and integrating Eq. 14 for the three cases, the modal masses are obtained and given in Table 1.

Table 1. The Modal Mass of the First Four Mode

Stiffness	Modal Mass (M_j^*)			
Ratio	First Mode	Second Mode	Third Mode	Fourth Mode
Case 1: $k_1 = 2k_2$	**0.5M**	**0.5M**	**0.5M**	**0.5M**
Case 2: $k_1 = k_2$	**0.589M**	**0.516M**	**0.664M**	**0.505M**
Case 3: $2k_1 = k_2$	**0.667M**	**0.667M**	**0.667M**	**0.667M**

It can be seen from Table 1 that

- the stiffness ratios diversify up to 300% while the modal masses change up to 33%.
- the modal masses are constant for Case 1 and Case 3 while the modal masses vary with different modes for Case 2 for the first four modes.

3.2 Fundamental frequency

The solution of the eigenvalue equation (Eq.4) provides a relationship between two unknowns, the frequency and the axial stiffness of the cross section. Therefore either the frequency or the axial stiffness should be determined using an alternative means, such as experiment. A method for the indirect measurement of human whole-body frequency[2] provided a way to obtain the human body frequency without using a shaking table. The test set-up is basically a simply supported reinforced concrete beam. The fundamental frequency of a human body can be calculated based on the frequency measurements of the bare beam and the human occupied beam, and expressed in the following form:

$$f_h = \sqrt{\frac{f_2^2 - f_s^2}{1 + \frac{M_h}{M_s} - \frac{f_s^2}{f_2^2}}} \qquad (16)$$

Where M_h and M_s are the modal masses of the human body and the test beam respectively, and f_h, f_s and f_2 are the fundamental frequencies of the human body, the bare beam and the measured frequency of the human occupied beam. The fundamental frequency and the modal mass of the beam are 18.68 Hz and 107.5 kg respectively. Four people were tested[2]. The body weight M, the measured frequency, f_2, and the calculated fundamental frequency of human body, f_h, corresponding to three different modal masses of the human body are listed in Table 2.

Table 2. Indirectly Measured Fundamental Frequency of Standing People

	Weight (M) (kg)	Measured Frequency of the human occupied beam (f_2)	Modal Mass		
			0.5M (Case 1)	0.589M (Case 2)	0.667M (Case 3)
P1	63.5	20.02	**11.05**	**10.42**	**9.96**
P2	79.0	20.51	**11.55**	**10.90**	**10.42**
P3	82.5	20.51	**11.38**	**10.73**	**10.25**
P4	95.5	21.00	**11.87**	**11.21**	**10.72**

It can be seen from Table 2 that

- the variation of the modal mass is 33% while the variation of the body frequency is about 10% between the maximum and the minimum values.
- The maximum difference of weight between individuals reaches 50% while the maximum difference of frequency is less than 8%.
- The calculated human body frequency based on one measurement depends on a correct value of the modal mass of the body. However, the difference of the body frequency between individuals for any selected modal mass is similar.
- Case 1 provides the stiffest human body model while Case 3 gives the most flexible.

3.3 Axial stiffness

Based on the solutions of the eigenvalue equations (Eqs. 8,10 and 12) and Eq.4, the axial stiffness of the human body can be determined using the following formula:

$$\bar{k}_i = \frac{k_i}{L_i} = \frac{\omega^2 m_i L_i}{(b_i L_i)^2} \qquad (17)$$

For the upper and lower parts the axial stiffness can be expressed as follows:

$$\bar{k}_1 = \frac{\omega^2 M}{3(b_1 L_1)^2} \quad \text{and} \quad \bar{k}_2 = \frac{2\omega^2 M}{3(b_2 L_1)^2} \qquad (18)$$

For the four people the body axial stiffnesses are listed in Table 3

Table 3. Body Axial Stiffness of Human Body for Studied Cases

	Case 1 (kN/m)		Case 2 (kN./m)		Case 3 (kN./m)	
	Lower($\bar{k}_1$)	Upper($\bar{k}_2$)	Lower($\bar{k}_1$)	Upper($\bar{k}_2$)	Lower($\bar{k}_1$)	Upper($\bar{k}_2$)

P1	372.2	186.1	268.5	268.5	245.3	490.6
P2	505.9	252.9	365.5	365.5	334.0	668.1
P3	512.8	256.4	369.9	369.9	337.6	675.1
P4	645.9	322.9	467.4	467.4	427.3	854.8

It can be seen from Table 3 that

- The body axial stiffness varies significantly for the four test people. The variation reaches 75% regardless of the studied cases, or the stiffness distributions.
- The stiffness of the lower part in Case 1 is about 50% bigger than that in Case 3 while the stiffness of the upper part in Case 1 is over 160% less than that in case 3. This observation is true for each individual.

3.4 Higher Frequencies

Based on Eq.18, the expression for obtaining the higher frequencies of the human body is:

$$f_j = \frac{b_j L_1}{2\pi}\sqrt{\frac{3}{M}\frac{k_1}{L_1}} = \frac{b_j L_1}{b_1 L_1} f_1 \qquad j = 2,3,4\cdots \tag{19}$$

The values of $b_j L_1$ can be found in Section 2.3 for three studied cases. The first three higher frequencies of a human body for the three cases and the four test people are listed in Table 4.

Table 4. The first three frequencies of human body for three studies cases and four people

	Case 1			Case 2			Case 3		
	f_2	f_3	f_4	f_2	f_3	f_4	f_2	f_3	f_4
P1	55.25	77.35	121.6	35.85	58.02	81.26	40.88	60.80	91.72
P2	57.75	80.85	127.1	37.50	60.69	85.00	42.76	63.60	95.96
P3	56.89	79.65	125.2	36.92	59.75	83.67	42.07	62.57	94.39
P4	59.35	83.09	130.6	38.59	62.42	87.42	43.99	65.43	98.72

The calculated higher frequencies in Table 4 show that

- The difference of higher frequencies between individuals is small, similar to the fundamental frequency. This is almost independent of the studied cases, or the distribution of the body stiffness.
- The difference of higher frequencies between different cases are significant, i.e. the assumption of the stiffness distribution significantly affects the actual stiffness of the human body.

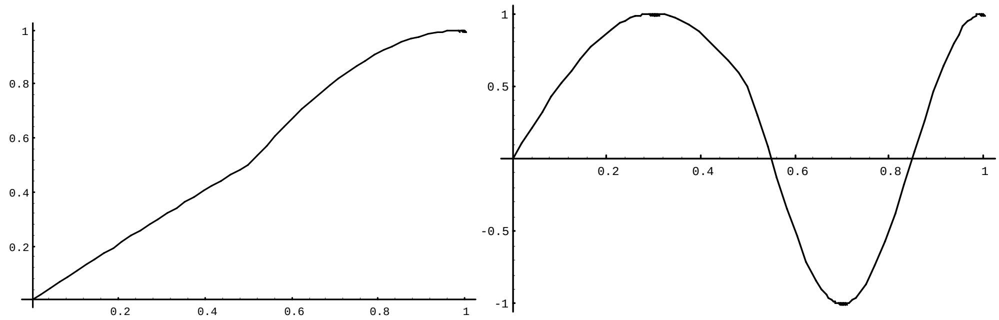
3.5 Mode Shapes

The human body response can be expressed as the summation of response of each mode. The mode shapes for the studied three cases are given in Eqs.(9, 11 and 13). Substituting the values of $b_j L_1$, four modes are defined and shown in Figs.2-4.

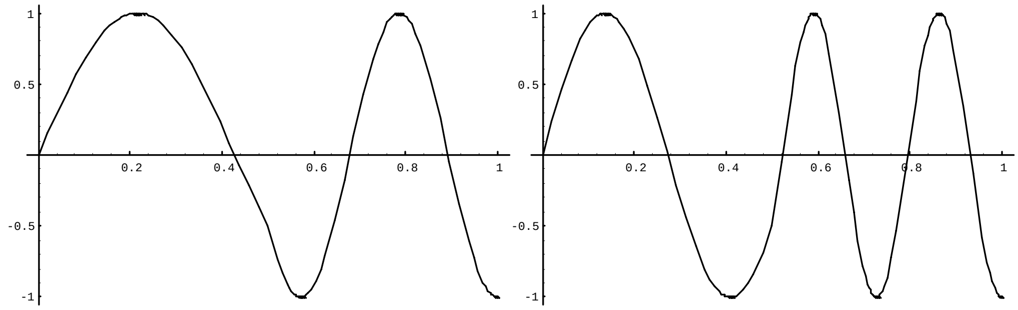
Comparing these mode shapes for the three cases, it can be observed that

- The fundamental modes in the three cases are similar, and show that all parts of the human body vibrate in the same direction and the top of the body has the maximum movement. Reproducing the discrete model proposed by Nigam[5], the above characteristics of the fundamental mode are also observed.
- For the higher modes the mode shapes are similar between Case 2 and Case 3 while the mode shapes in Case 1 are notably different from those in other two cases. The shapes that have one or four intersections on the horizontal axis do not exist in Case 1.

- In Cases 2 and 3, the second mode shows that the top half of the upper part and the rest of the body move in the opposite directions. The top half of the lower part has the maximum movement in this mode.
- The shape of the second mode in Case 1 is similar to that of the third modes in the other two Cases. The lower part moves in the same direction as the top half of the upper part while the movement of the lower half of the upper part is opposite to that of the top half.

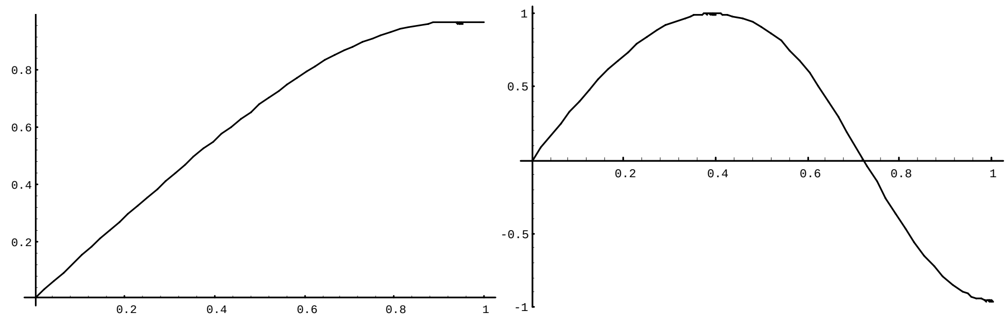


The First Mode The Second Mode

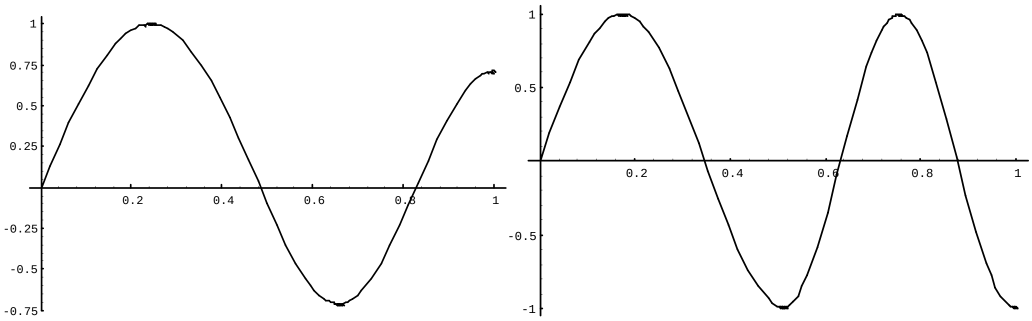


The Third Mode The Fourth Mode

Fig.2 The Mode shapes of Case 1 ($k_1 = 2k_2$)

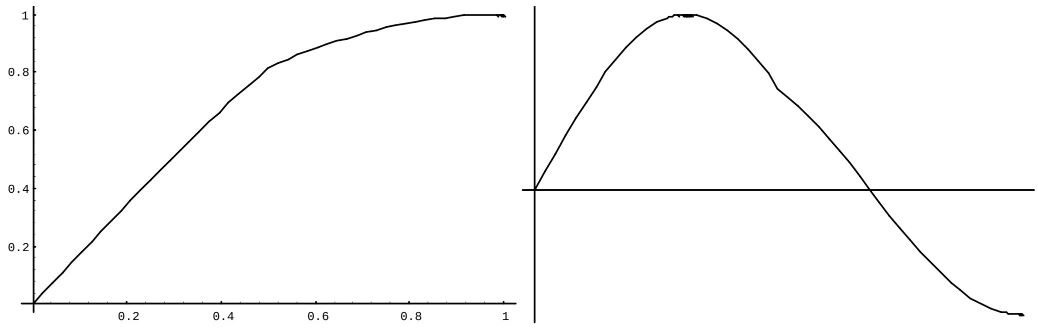


The First Mode The Second Mode

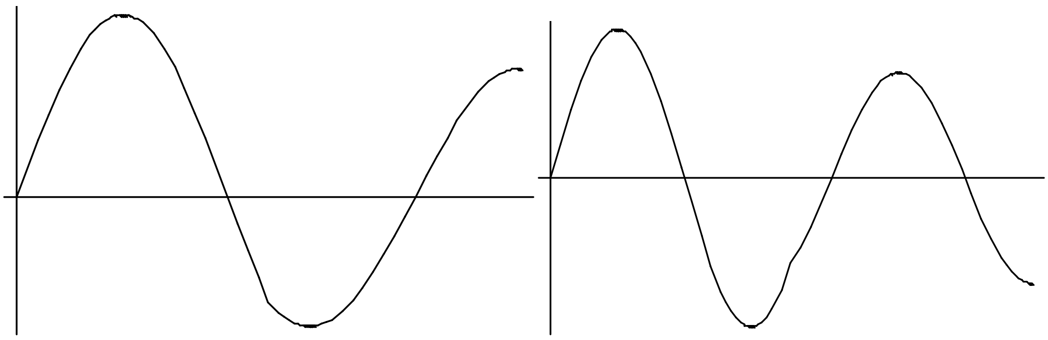


The Third Mode The Fourth Mode

Fig.3 The Mode Shapes of Case 2 ($k_1 = k_2$)



The First Mode The Second Mode



The Third Mode The Fourth Mode

Fig.4 The Mode Shapes of Case 3 ($2k_1 = k_2$)

4. DISCUSSION

4.1 Human Models

To model the dynamic characteristics of people, investigators have proposed various lumped parametric vibratory models consisted of discrete masses, springs and viscous dashpots.

The simplest one is the 2 DOF model proposed by Coermann[8] and a human vibration simulator was produced[4]. The development of this model was based on correlating the model parameters to the results of experimental investigations into the mechanical impedance of the human body. The idealisation of the human body is shown in Fig.5. This model has been adopted by ISO 5982 for deriving the driving point impedance of the human body at sitting and standing positions. The parameters of the model are given in Table 5. The data in the Table indicates that the Mass 2 consists of the masses of the head and the upper torso and the Mass 1 represents the rest of the body.

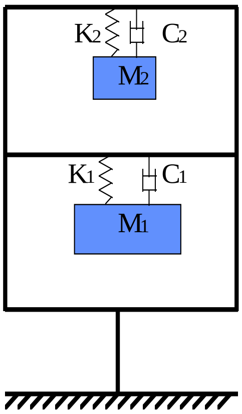


Fig.5 2 DOF ISO Model

Table 5 Parameters of the 2 DOF ISO Model for Standing people

Element	Mass (kg)	Stiffness (kN/m)	Damping (kN s/m)
1	62.0	62.0	1.46
2	13.0	80.0	0.93
Note: The total body mass is 75.0 kg.			

This 2 DOF model is actually two independent SDOF systems rather than a 2 DOF system because there is no connection between two masses except the rigid frame. This model suggests that the vibration of the human head and the upper torso is independent of the vibration of the rest of the body. Although this model provided two frequencies that match the measurements, this model is conceptually incorrect.

A more complex model was proposed by Nigam and Malik [5]. The model is a 15 DOF mass-spring system. The more sophisticated the model, the more parameters to be determined and the more difficulties involved. Using this model, up to 15 modes and frequencies of the human body can be calculated. The accuracy of this type of model is always questionable. When considering human response to vibration, this model has limited practical value because the model does not include any damping capability.

In this paper, a continuous human body model at the standing position is proposed. Simplifications are made to neglect local vibrations of any part of the body and the differences between different segments in the upper and lower parts. Therefore this model is valid for studying the global vibration of a standing person. The advantages of using this model in the study of the dynamic characteristics and the response of the human body to vibration are:

- The human body response to vibration can be calculated as the summation of the responses of a few single degree-of-freedom systems according to their respective modes.
- The model has less unknown parameters to be determined than a discrete model.

4.2 Theoretical and experimental methods

The major problem with the theoretical study of the human body is the determination of the basic input parameters, whilst with the experimental study the major problem is the evaluation of mode shape and higher order modes. However, the theoretical study can be used to calculate mode shape and higher modes, whilst the experimental study can be adopted to determine the basic characteristics of the human body. Therefore, a combined use of both methods may provide a means to overcome their respective weaknesses.

Based on the assumption in Section 2.1, the proposed theoretical model has two independent and unknown parameters, k_1 and k_2. When Eq.16 and the related experiments are provided, the unknowns are reduced from two to one, i.e., the ratio of the axial stiffness or the modal mass of the human body. Therefore the sensitivities of the frequencies and mode shapes of the human body to the modal mass or the ratio of the axial stiffness are studied. Using the proposed model, the human body response at the standing position to the vertical vibration can be investigated and the body response in each mode can be identified. In order to obtain the correct ratio of the axial stiffness or the modal mass of the human body, another relationship should be provided and associated tests may be required.

4.3 Human-structure vibration

In the study of the human response to structural vibration and structural vibration involving people, the human body and the structure should be treated as a global system[9]. For some structures this topic is particularly important:

- Office floors where sitting people may be disturbed by floor vibration induced by other people walking or jumping.
- Grandstands where a crowd of people is involved. Both the structural safety and human comfort should be considered.

The structural vibration of these structures is dominated by their fundamental mode and usually the fundamental frequencies of these structures are below 10 Hz. The structural vibration is often induced by human movements. The human induced loads have a range of frequencies and the significant ones are less than 10 Hz. It has been noted in this study that the second frequency is about four, three and five times the fundamental one in the studied three cases respectively. To consider the global effect of human response to structural vibration and the structural vibration where people are involved, only the response of the fundamental mode of the human body need to be taken into account. Therefore, a human body can be represented as a single degree of freedom system, according to its fundamental mode, on a structure for the study of the human-structure vibration.

5. CONCLUSIONS

A continuous model of the vertical vibration of the human body model in a standing position is proposed in this paper. The model can be used to investigate modes and frequencies of a human body and to study the human body response subject to given loads. An unknown, the ratio of the axial stiffness or the modal mass, is included in this model, therefore, a parametric study is conducted.

The main conclusions drawn from this study are:

1. The modal mass of the human body can be calculated based on the proposed model and this provides a theoretical basis for studying the human-structural vibration. Further preliminary tests suggest that the modal mass of the human body is about two thirds the whole body weight. This requires further verification.

2. When the assumed ratio of the axial stiffness of the upper and lower part of the human body varies up to 300%, the corresponding modal mass fluctuates about 33% and the human body frequency changes about 10%.
3. The maximum difference of body weight between tested individuals varies up to 50% while the maximum difference of the fundamental frequency of human bodies is less than 8%.
4. The fundamental mode of the human body shows that all parts of the human body vibrate in the same direction and the top of the body has the maximum movement regardless of the differences between individuals and between the ratios of axial stiffness of the proposed model.

The further study is to determine the unknown in the model and the critical damping of the model, and then to investigate the human body response to given loads.

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