

The influence of human motion state on human-structure interaction

Zhifan Han^{1*}, Guohua Lu^{1,2}, Rudong Li²

¹Construction Institute, Guangdong Polytechnic College, Zhaoqing, Guangdong, 526000, China

² Zhaoqing Division, Gong Cheng Management Consulting Co., Ltd., Zhaoqing, Guangdong, 526000, China

Abstract. Under pedestrian load, significant vibration and comfort problems are easy to arise for large-span low-frequency structures so that human-structure interaction should be considered in the design. However, different human motion states have different human modal parameters, which makes the design more difficult. The Spring-Mass-Damper (SMD) model is used to conduct numerical simulation experiments on 6 box beams with different fundamental frequencies in 4 different human motion states, based on which the dynamic characteristics of the structure under 30 working conditions are compared and analyzed. It is recommended to use the modal parameters of the standing human body in the vibration comfort design, and use the modal parameters of the human body at normal walking speed for the design of the low-frequency structure.

1 Introduction

Large-span, light and flexible structural systems are widely used in large public buildings such as theaters, stadiums, pedestrian bridges, and airports. Such structures have low fundamental frequency and damping ratio, and the interaction between people and structure is obvious, and significant vibration is prone to appear under pedestrian loads. The problems of structural failure, casualties and discomfort caused by human-induced vibration have become increasingly prominent, bringing economic losses and social impacts that cannot be underestimated. After the London Millennium Bridge incident^[1], the influence of human-structure interaction on structure has attracted much attention, and academia has launched a comprehensive research on this.

The research of human-structure interaction mainly revolves around two aspects (human-structure coupling system dynamic model and human dynamic parameters). Commonly used human-structure coupling system dynamic models include MD model, SMD model and MMSD model^[2-4]. The MD model does not take into account the influence of human modal stiffness, so there are limitations in use. Both the SMD model and the MMSD model take into account the effects of human modal quality, modal stiffness and modal damping, and reflect the human-structure interaction reasonably, and are suitable to be dynamic models of the human-structure coupling system. Research shows that the calculation results of SMD model and MMSD model are basically the same, and the additional mass in the MMSD model has little effect on the dynamic response of the structure. Compared with MMSD, the application of SMD model is

easier and more suitable for structural designers^[4]. The determination of human body dynamics parameters is another important point in determining the human-structure interaction. In recent years, researchers have tried to identify human dynamics parameters through the frequency response function expression of the human-structure coupling system combined with the measured values. Y. Matsumoto and M.J. Griffin gave the dynamic parameters of a standing human body^[2], J. Alonso, A. Saez, et al. gave the dynamic parameters of pedestrians^[5]. The pedestrian dynamic parameters given by F. Silva, H. Brito, et al. vary with pedestrian quality and stride frequency^[6]. It can be seen that different human body motion states have different human body dynamic parameters so that the human-structure interaction is different, which causes difficulties for structural designers to use human body dynamic parameters.

In summary, when conducting human-structure mutual analysis, the SMD model is easy for structural designers to use and meets engineering accuracy requirements. However, the change of the human body motion state brings changes to the human body dynamic parameters, which makes the design more complicated, and the designer cannot determine how to use various parameters. In this regard, this article uses the dynamic parameters of the standing human body in literature [2] and the pedestrian dynamic parameters in literature [6], and employs the SMD model to analyze the impact of changes in the human body motion states on the human-structure interaction in order to optimize the design.

*Corresponding author's e-mail: hanzfhanzf@163.com

2 Human-structure coupling system motion equations and pedestrian modal parameters

The human body is a mechanical system with mass, rigidity and damping, which will interact with the structure to form a human-structure coupling system. The SMD model simulates pedestrians as a spring-mass-

damped system (as shown in Figure 1) and takes into account the influence of human modal stiffness, mass and damping on the structure, making it easy for structural designers to use by meeting engineering accuracy requirements. When the human body motion state changes, the pedestrian modal parameters change accordingly. To predict the influence of the human motion state on the human-structure interaction, the motion equation of the coupled system needs to be established first.

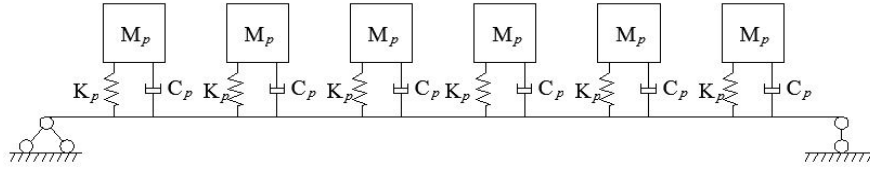


Figure 1. Pedestrian SMD model.

2.1 Pedestrian SMD model-structure coupling system motion equation

According to the principle of structural dynamics, the dynamic equation of the human-structure coupling system is:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{P(t)\} \quad (1)$$

Where : $[M] = \begin{bmatrix} I_{n \times n} & 0_{n \times 1} \\ 0_{n \times 1} & M_p \end{bmatrix}$, $[C] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_p \end{bmatrix}$, $[K] = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_p \end{bmatrix}$, M_p , K_p , C_p are the modal mass, stiffness and damping of pedestrians respectively.

Then the free vibration equation of the human-structure coupling system is:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = 0 \quad (2)$$

Suppose the solution of equation (2) is

$$x = \varphi e^{\lambda t} \quad (3)$$

Among them, λ is the eigenvalue, and φ is the eigenvector.

Substituting (3) into (2) to get:

$$(\lambda^2[M] + \lambda[C] + K)\varphi = 0 \quad (4)$$

The eigenvalues obtained by the solution are complex numbers, and the corresponding eigenvectors are also complex numbers. The natural frequency and damping ratio of the system are:

$$f_r = \frac{1}{2\pi} |\lambda_r| \quad r = 1, 2, \dots, n \quad (5)$$

$$\zeta_r = \frac{-Re(\lambda_r)}{|\lambda_r|} \quad r = 1, 2, \dots, n \quad (6)$$

2.2 Modal parameters of SMD model

The human body's motion state is different, so the modal parameters are different. When standing, the modal parameter has higher modal quality, stiffness and damping. As the step frequency changes, the three modal parameters change. This article adopts the calculation method of normal standing human modal parameters in literature [2]: $m_p = 1.03M(kg)$, $c_p = 51.6M(Ns \cdot m^{-1})$, $k_p = 1340M(N \cdot m^{-1})$, where M is the body mass. The calculation method of pedestrian modal parameters in literature [6] is adopted, as shown in Equation 7, where f_h is pedestrian walking frequency.

$$m_p = 97.082 + 0.25M - 37.518f_h \quad (kg)$$

$$c_p = 29.041m_p^{0.883} \quad (Ns \cdot m^{-1}) \quad (7)$$

$$k_p = 30351.744 - 50.261c_p + 0.035c_p^2 \quad (N \cdot m^{-1})$$

Take the body mass $M=70kg$, and the pedestrian walking frequency f_h is 1.7Hz, 2.0 Hz and 2.3 Hz respectively representing slow speed walking, normal speed walking, fast speed walking, whose modal parameters are shown in Table 1.

Table1. Modal parameters of pedestrian SMD model.

Human motion state	$m_p(kg)$	$c_p(Ns \cdot m^{-1})$	$k_p(N \cdot m^{-1})$
normal standing	72.1	3612	93800
Slow-speed walking	52.55	960.04	14357.79
Normal-speed walking	41.30	775.99	1245.34
Fast-speed walking	30.04	585.91	12918.53

3 Human-structure interactions in different human motion states

This section uses ANSYS finite element software to establish a human-structure coupling system. Using the modal parameters of the pedestrian SMD model in the 4 human motion states in Table 1 and 6 large-span box beams with different fundamental frequencies, a total of 30 working conditions are compared. The crowd density

Table2. Box beam section size

Section	H(m)	W(m)	t_1 (m)	t_2 (m)	f_s (Hz)
H0.5	0.5	2	0.05	0.02	1.947
H0.7	0.7	2	0.05	0.02	2.762
H0.9	0.9	2	0.05	0.02	3.547
H1.1	1.1	2	0.05	0.02	4.304
H1.3	1.3	2	0.05	0.02	5.032
H1.5	1.5	2	0.05	0.02	5.731

In order to explore the influence of changes in human motion state on the dynamic characteristics of the box beam. Firstly, modal analysis of H0.5-H1.5 box beams is implemented to obtain the dynamic characteristics of the empty bridge. Then, modal analysis of the box beam considering the human-structure interaction is carried out to compare changes in the dynamic characteristics of the structure. Pedestrian modal parameter is taken from Table

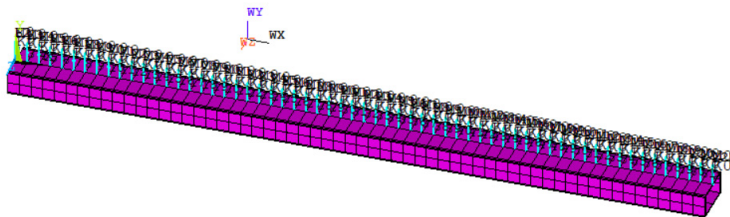


Figure 2. Finite element model of human-structure coupling system

3.1 The influence of changes in human motion state on the structural fundamental frequency

Figure 4 shows the comparison between the fundamental frequency of the structure with human-structure interaction and the fundamental frequency of the unloaded structure. The comparison shows that: (1) The standing human body has a great influence on the structural fundamental frequency, no matter whether it is high-frequency structure or low-frequency structure, and the human-structure interaction is obvious. Fundamental frequency of human-structure coupling system maintains around natural frequency of standing human body and will not lead to the reduction of low frequency. (2) The human body at the three walking speeds has roughly the same impact on the structural fundamental frequency, and has a greater impact on the low-frequency structure, which reduces the fundamental frequency of the low-frequency structure but has basically no effect on the structure with a higher frequency ($f_s > 3.6$).

takes $0.5ped \cdot m^{-2}$ [7] the maximum density at which pedestrians can walk freely. The calculated span of the box beam is 30m, and both ends are simply supported, using Q345 steel. The box beam section size is shown in Table 2, the finite element model of the human-structure coupling system in Figure 2, and the box beam section in Figure 3. The fundamental frequency of the structure is f_s , and the frequency ratio μ is the natural frequency of the human body divided by the fundamental frequency of the structure.

1 in 4 different motion states. Take the frequency change factor α as the structural fundamental frequency of empty bridge divided by the structural fundamental frequency with pedestrian influence, and take the damping ratio change factor β as the structural damping ratio of empty bridge divided by the structural damping ratio with pedestrian influence.

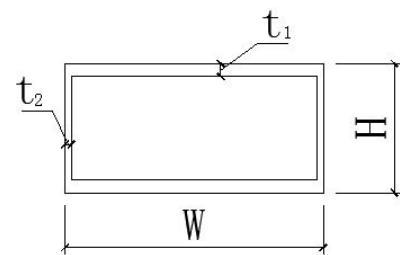


Figure 3. Box beam section form.

Figure 5 shows the influence of the human body at different walking speeds on the structural fundamental frequency, and shows the influence of the walking human body on the structural fundamental frequency when the frequency ratio μ is different. The comparison shows: (1) When the frequency ratio $\mu > 1.6$, the frequency change factor α is almost equal to 1. At this time, the influence of the walking human body on the structural fundamental frequency can be ignored. (2) The human body at normal walking speed ($f_k = 2.0$ Hz) has the greatest impact on the structural fundamental frequency. When the frequency ratio $\mu \in [1, 1.4]$, the structural fundamental frequency is significantly reduced.

3.2 The influence of changes in human motion state on structural damping ratio

Figure 6 shows the change rate of the structural damping ratio with human-structure interaction, and provides the influence of the human body in different motion states on the structural damping ratio. It can be seen from Figure 6

that: (1) The human body has roughly the same influence on the structural damping ratio in the four motion states. When the frequency ratio μ is smaller, the human body has a greater influence on the damping ratio. But with the increase of μ , the influence of the human body on the structural damping ratio is greatly reduced regardless of

the state of motion. (2) When $\mu < 1$, regardless of the motion states, the structural damping ratio will always increase. (3) When $\mu > 2$, β almost equals to 1. At this time, the influence of the human body on the structural damping ratio can be ignored.

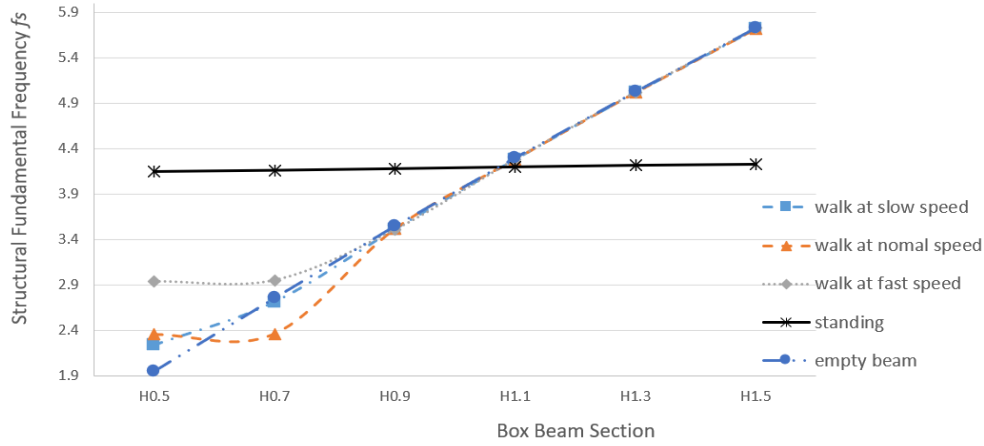


Figure 4. The influence of the human body in different motion states on the structural fundamental frequency.

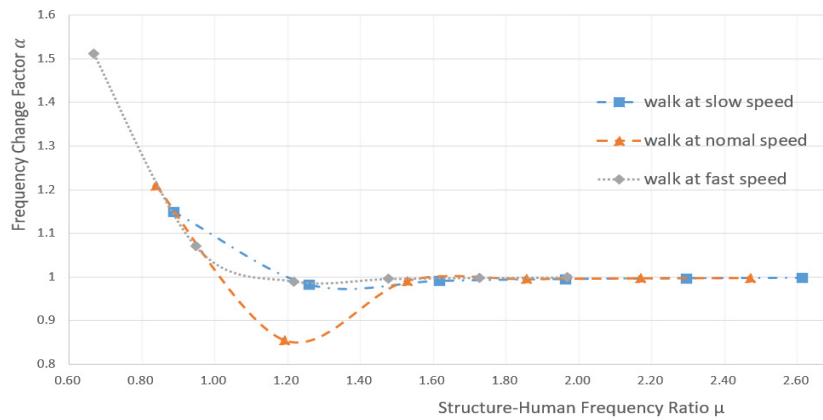


Figure 5. The influence of the human body at different walking speeds on the fundamental frequency of the structure.

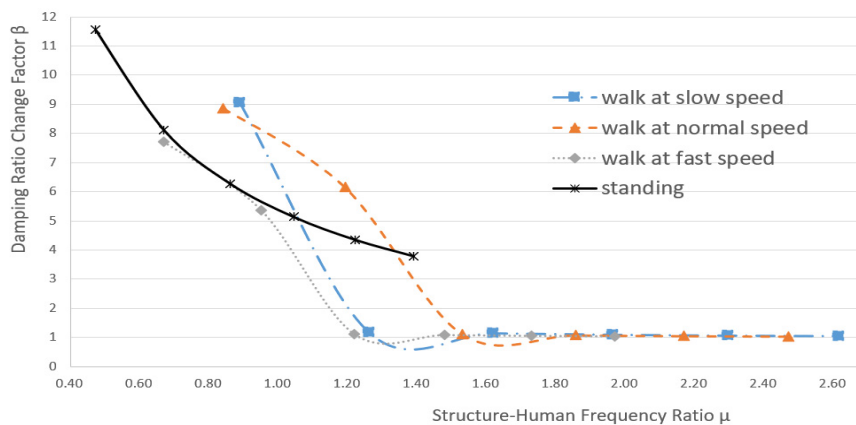


Figure 6. The influence of human body (in 4 different motions states) on structural damping.

4 Conclusion

In this paper, theoretical analysis and numerical simulation are combined to conduct numerical simulation

experiments on 6 box beams with different fundamental frequencies in 4 different human motion states. Based on this, the dynamic characteristics of the human-structure coupling system are studied in order to explore the influence of the human motion state on the human-

structure interaction is explored. The main conclusions are as follows:

1. When the frequency ratio $\mu < 1.6$ or the structural fundamental frequency $f_s < 3.6$, the structure is obviously influenced by the human body, and the dynamic characteristics of the structure change greatly, so the human-structure interaction should be considered in the structural design.

2. When the frequency ratio $\mu > 2.0$, influence of human body on the dynamic characteristics of the structure are limited, which can be ignored in the structural design.

3. The modal mass, stiffness, and damping of the standing human body are greater than those of the walking human body, and the influence on the structural fundamental frequency is significantly greater than that of the walking human body so that the structural fundamental frequency maintains near the natural frequency of standing human body, but will not reduce the frequency of the low-frequency structure. Since the structural fundamental frequency is close to the natural frequency of human body, it is suitable to use the modal parameters of standing human body in the vibration comfort design.

4. For low-frequency structures, the human body at normal speed walking has the greatest impact on the structure, which can significantly reduce the structural fundamental frequency to approximate the pedestrian step frequency. Therefore, in the design of low-frequency structure, when the influence of human-structure interaction on the structure considered, it is suitable to use the modal parameters of the human body at normal speed walking.

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