Vertical human-induced vibration of pedestrian bridge

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Abstract: The double degrees-of-freedom (DOFs) parallel model is adopted to analyze static vertical human-induced vibration with the finite element analysis (FEA) method. In the first-order symmetric vibration mode, the periods of the spring-mass model gradually decrease with the increase in K_1 and K_2, but they are always greater than the period of the add-on mass model. Meanwhile, the periods of the spring-mass model decrease with the decrease in m_1 and m_2, but they are always greater than the period of the hollow bridge model. Since the human's two degrees-of-freedom vibrate in the same direction as that of the bridge mid-span, the existence of human's rigidity leads to the reduction in the rigidity of the spring-mass model. In the second-order symmetric vibration mode, the changes of rigidity K_2 and mass m_2 result in the disappearance or occurrence of some vibration modes. It can be concluded that compared with the spring-mass model, the results of the add-on mass model lean to lack of safety to the structure; besides, the DOF with a smaller ratio of mass to rigidity plays the chief role in the vibration of the structure.

Key words: human-induced vibration; spring-mass model; double degrees-of-freedom (DOFs) parallel model

I n recent years, excessive vibrations from high traffic on steel structure pedestrian bridges have become increasingly evident[1−2]. When everyone on the structure is in the posture of sitting, standing or other similar conditions, the loading effect on the structure is static. For most designs of structures, static loading is empirically treated to be uniformly-distributed. Even taking into account the dynamic effects of the static loading, the pedestrian loading is simply treated as an add-on mass of the structure[3]. Though the add-on mass model is widely accepted and incorporated into the design specifications in many countries, it is quite obvious that this model will reduce the natural frequency of the structure vibration, while some other model parameters, such as rigidity and damping, do not change[4]. However, the actual measurements indicate that it is not the case. Static loading on the structure can not only change the natural frequency of the structure vibration, but also alter the rigidity of the structure due to the intrinsic rigidity of human bodies[5]. Therefore, an objective method for the static pedestrian loading, the spring-mass model, should be applied to analyze the original structure.

For the purpose of simplicity, this paper only studies the one-man model. For the bridge structure, static pedestrians are normally in the posture of standing. Thus, it is necessary to build a reasonable and workable vertical vibration linear model with a man in a standing posture before conducting the study of the vertical vibration on a pedestrian bridge[6].

1　Mechanical Model of Static Human-Induced Vibration

The double degrees-of-freedom parallel model, as shown in Fig. 1, has less interference between the two degrees of freedom. It is simple, and it can facilitate the implementation of the mechanical model. This model is also recommended by the International Organization for Standardization and is thus adopted to research the vertical human-induced vibration in this paper. Based on the physical test on a human body's vibration and using the parameter averaging method, we obtain the human body's parameters as shown in Tab. 1[7−8]. In this table, K_1 is the rigidity of DOF 1; m_1 is the mass of DOF 1; K_2 is the rigidity of DOF 2; m_2 is the mass of DOF 2; m_0 is the mass of the static part of the human body.
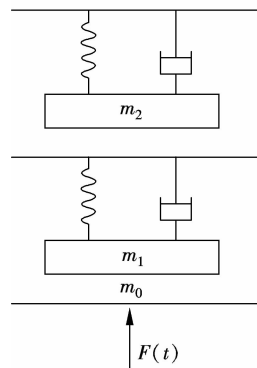

Fig. 1　Double DOFs parallel model

Tab. 1　Human body parameters obtained by parameter averaging method

Parameter	Mean μ	Standard deviation σ	Minimal value	Maximal value
$K_1/(\text{kN} \cdot \text{m}^{-1})$	32.1	6.0	22.6	47.5
m_1/kg	28.6	4.7	21.2	40.4
$K_2/(\text{kN} \cdot \text{m}^{-1})$	80.5	20.5	36.9	123.6
m_2/kg	21.9	6.6	9.2	43.7
m_0/kg	8.6	3.5	4.6	17.1

2　Example on Calculation of Human-Induced Vibration for Pedestrian Bridge

2.1　Model establishment

Fig. 2 is the finite element analysis model of a pedestrian bridge. The bridge has a span of 30 m with a vector height

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of 3 m and belongs to a plane truss system. The vertical vibration periods are illustrated in Tab. 2.

According to the range of variable parameters in Tab. 1, we can classify these parameters into several groups (see Tab. 3) and input them into the FEA bridge model. Since m_0 is completely connected to the bridge model in a rigid manner without independent freedom, m_0 is not included as a variable.
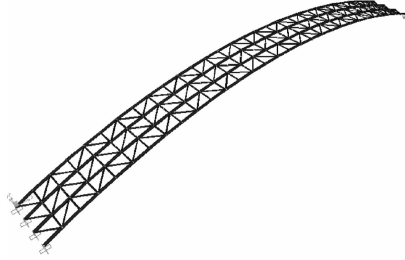

Fig. 2 FEA model of a pedestrian bridge

Tab. 2 Structural dynamic properties

Natural period/s	Vibration mode
0. 280 34	First-order symmetry
0. 109 05	Second-order symmetry

Tab. 3 Man's model parameter values

$K_1/(\text{kN} \cdot \text{m}^{-1})$	m_1/kg	$K_2/(\text{kN} \cdot \text{m}^{-1})$	m_2/kg
22	21	37	9. 18
27	25	57	16. 08
32	29	77	22. 98
37	33	97	29. 88
42	37	117	36. 78
47	41	137	43. 68

2. 2 Calculation, analysis and comparison

Compared with the original shape of the bridge model (see Fig. 3(a)), there are three kinds of vibration shapes in each mode. The first is the two DOFs of the human body vibrating in the same direction as the structure; the second is the two DOFs of the human body vibrating in the reverse direction to the structure; and the third vibration shape represents the one DOF vibrating in the same direction as the structure and the other DOF vibrating in the reverse direction to it. Both the first-order symmetry vibration modes (see Fig. 3 (b)) and the second-order ones (see Fig. 3(c)) include the three kinds of vibration shapes mentioned above. However, whether the three kinds will appear in the spring-mass model depends upon the mass, rigidity and other parameters of the double DOFs parallel model and the bridge model.

According to the finite element analysis, the changes in parameters K_1, K_2, m_1, m_2 in the double DOFs parallel model will lead to the changes in the vibration mode and the vibration period in the spring-mass model. By investigating the trend of curves in Fig. 4 to Fig. 7, we can sum up the following rules.

The periods in Fig. 4(a) and Fig. 5(a) gradually decrease with the increase in K_1 and K_2, but they are always greater than the period of the add-on mass mode (That is 0. 287 98 s). Meanwhile, the curve becomes flatter with the increase in rigidity since the model approaches the add-on mass model when K_1 and K_2 tend to infinity. Furthermore, since the human's two degrees-of-freedom vibrate in the same direction as that of the bridge mid-span, the existence of human's rigidity leads to the reduction in the rigidity of the spring-mass model; thus the periods are always
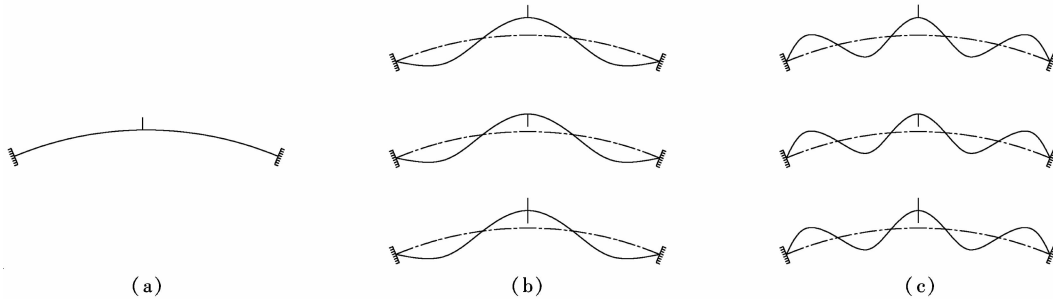

Fig. 3 Vibration mode of spring-mass model. (a) Original shape; (b) First-order symmetry vibration mode; (c) Second-order symmetry vibration mode
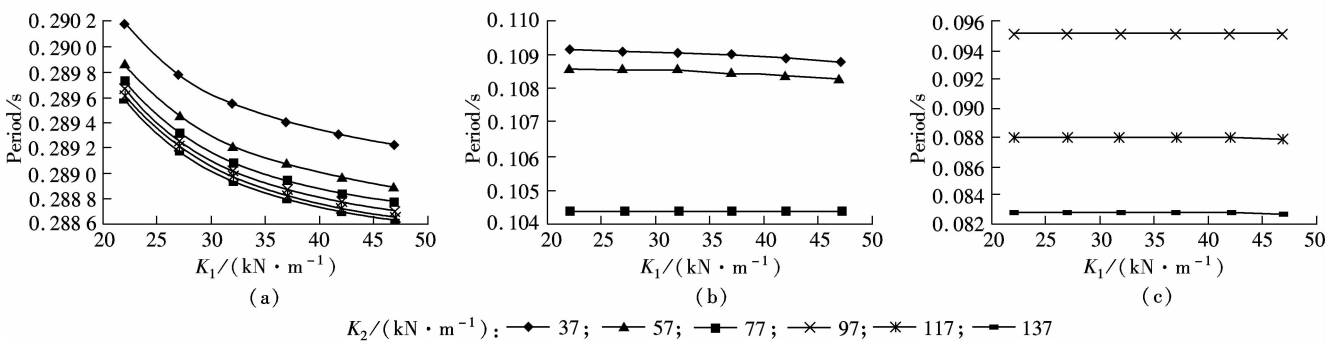

$K_2/(\text{kN} \cdot \text{m}^{-1})$: ◆ 37; ▲ 57; ■ 77; ✕ 97; ✳ 117; — 137

Fig. 4 Curves of period vs. K_1. (a) First-order symmetric vibration mode (both same); (b) Second-order symmetric vibration mode (both reverse); (c) Second-order symmetric vibration mode (one same, one reverse)

Fig. 5 Curves of period vs. K_2. (a) First-order symmetric vibration mode (both same); (b) Second-order symmetric vibration mode (both reverse); (c) Second-order symmetric vibration mode (one same, one reverse)
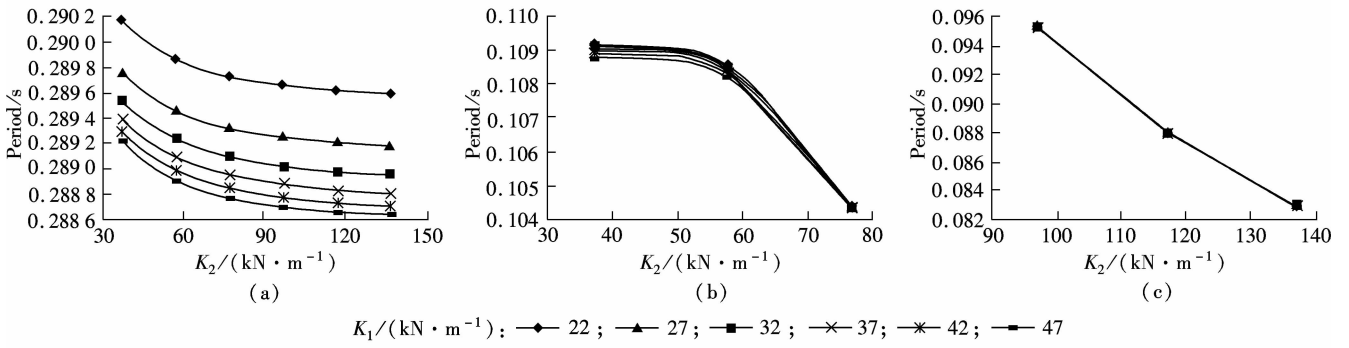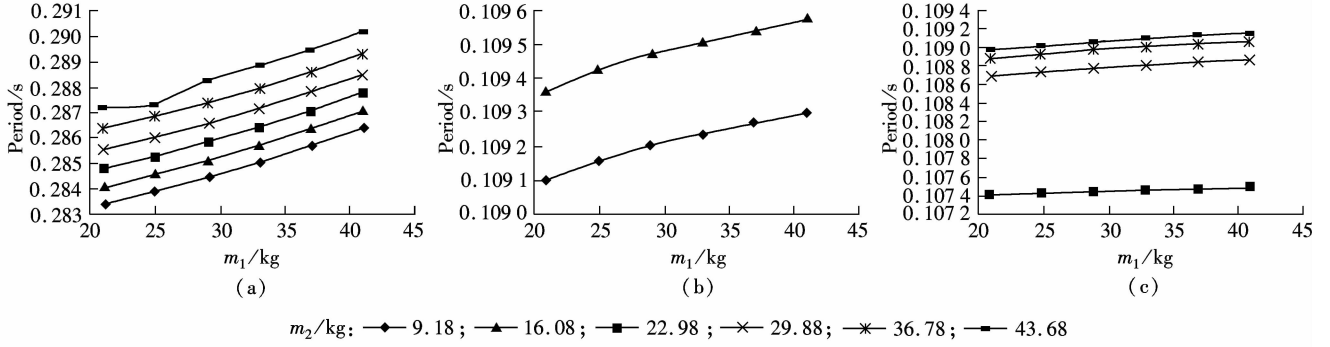

Fig. 6 Curves of period vs. m_1. (a) First-order symmetric vibration mode (both same); (b) Second-order symmetric vibration mode (one same, one reverse); (c) Second-order symmetric vibration mode (both reverse)

Fig. 7 Curves of period vs. m_2. (a) First-order symmetric vibration mode (both same); (b) Second-order symmetric vibration mode (one same, one reverse); (c) Second-order symmetric vibration mode (both reverse)
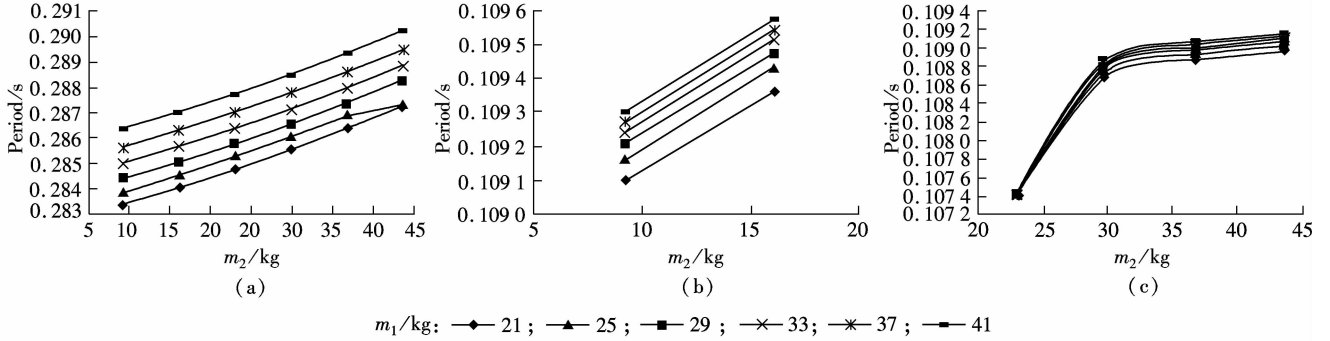
greater than those of the add-on mass model. As a result, all the curves in Fig. 4(a) and Fig. 5(a) are above the asymptote where the period is 0. 287 98 s. Figs. 4(b) and (c) and Figs. 5(b) and (c) demonstrate the change in the period of the second-order symmetric vibration mode with the change in human's rigidity. According to Fig. 5, with the increase in rigidity K_2, not only does the period of the second-order symmetric vibration mode drop rapidly, but also the vibration mode changes; i. e., from the second vibration shape to the third one (see Fig. 3(c)), which exactly demonstrates that the change in rigidity results in the disappearance or occurrence of some vibration modes. On the other hand, the increase in K_1 may have little influence on the period of the second-order symmetric vibration mode.

The periods in Fig. 6(a) and Fig. 7(a) decrease with the

decrease in m_1 and m_2, but they are always greater than the period of the hollow bridge model (That is 0. 280 34 s). Meanwhile, it can be seen that the curve becomes flatter with the decrease in mass since the model is converted to the hollow model when m_1 and m_2 tend to zero. Figs. 6(b) and (c) and Figs. 7(b) and (c) demonstrate the change of period of the second-order symmetric vibration mode with the change in the mass of the human. According to Fig. 7, with the increase in mass m_2, not only does the period of the second-order symmetric vibration mode increases, but also the vibration mode changes; i. e., from one same, one reverse to both reverse, which again demonstrates that the change in the mass will result in the disappearance or occurrence of some vibration modes. Furthermore, the increase in m_1 may increase the period of the second-order symmetric vibration mode.

3　Conclusion and Future Work

Compared with the add-on mass model, the spring-mass model can more precisely illustrate the influence of the human body on the structure. The period of the spring-mass model is greater than that of the add-on mass model, so the results of the add-on mass model will lean to lack of safety for the structure. When the double DOFs parallel model is adopted to simulate the model of the static human body, the independent movement of two DOFs will result in the complication of the research, but the DOF with a smaller ratio of mass to rigidity will play a chief role in the vibration of the structure.

This paper only involves the activity of one man, while the effect of a crowd is not considered. The effect of a crowd is not just the simple sum of multiple individuals, which may require the involvement of probability theory for further expansion in the future[9]. Also, during the analysis of the structure, the majority of attention is paid to the effects of one man on the structure. It would be interesting to consider the effect of structural vibration on human's body to reflect the people-oriented design philosophy[5].

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人行桥的竖向人致振动

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摘要:运用双自由度并联模型对静态人体的竖向人致振动问题进行有限元分析.在一阶对称振型中,弹簧质量模型的周期随着刚度 K_1 和 K_2 的增大而逐渐减小,但总大于附加质量模型的周期;同时又随着质量 m_1 和 m_2 的减小而逐渐减小,但也总大于空桥模型的周期;且由于人体与桥梁跨中运动方向相同,因此人体刚度的存在降低了弹簧质量模型的刚度.在二阶对称振型中,刚度 K_2 和质量 m_2 的变化导致了某些振型的出现和消失.进而可以得出结论:附加质量模型相比弹簧质量模型而言,在结构设计方面将偏于不安全;此外,双自由度并联模型中的质量刚度比值较小的自由度对结构振动将起主导作用.
关键词:人致振动;弹簧质量模型;双自由度并联模型
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