The Influence of Human-structure Interaction on Structural Dynamic Properties

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Abstract. For large-span flexible structures, human-structure interaction is obvious, but designers do not have a clear understanding of whether human-structure interaction should be considered in structural design. In this paper, the pedestrian Spring-Mass-Damper (SMD) model and dynamic parameters are used to study the influence of human-structure interaction on structural dynamic properties by using ANSYS finite element calculation software to calculate and compare 70 working conditions. The results show that when the structure-human frequency ratio is less than 1 and slightly greater than 1, the human-structure interaction has a greater influence on the dynamic properties of the structure. As the structure-human frequency ratio increases, the influence of the human-structure interaction on the dynamic properties of the structure decreases. When the structure-human frequency ratio is greater than 2, the human-structure interaction can be ignored.

1. introduction
Large-span flexible structures with low damping and low natural frequency, such as large-span floors, pedestrian bridges, pedestrian corridors, and long cantilever structures, are widely used in public buildings. Normal people walking may cause structural vibrations of large-span flexible structures, and the human-structure interaction is obvious, which will adversely affect the comfort of pedestrians and safety of the structure. After events such as the Millennium Bridge[1] in the United Kingdom, the problem of human-induced structural vibration has received widespread attention, and scholars have carried out a lot of research in the field of human-structure interaction. In order to accurately and effectively analyze the human-structure interaction and predict its vibration, the key is to establish a human-structure interaction dynamic model and identify pedestrian dynamic parameters.

At present, there are mainly three ways to establish a dynamic model of human-structure interaction. The first is the MD model, which simulates pedestrians as mass-damper (MD) [2]. The second is the SMD model, which simulates the pedestrian as a spring-mass-damper (SMD) [3]. The third type is the MMSD model, which simulates the pedestrian as a mass-spring-damper-additional mass (MMSD)[4]. The application of the MD model is relatively simple, which is based on the assumption that pedestrians have changed the structural mass and damping, but the effect of the equivalent stiffness of the human body on the structure is not considered, so there are limitations in use. Both the SMD model and the MMSD model consider the effect of the equivalent stiffness and damping of the human body on the structure, and reflect the human-structure interaction more...
reasonably. The MMSD model considers the effect of the additional mass of the human body. It is more accurate in theory, but for the structural designers, the application is too complex, and it is more efficient to use the SMD model to consider human-structure interaction\cite{5}. The key to the application of the SMD model is to obtain the dynamic parameters of the human body. Researchers use the human-structure coupling system motion equation combined with the experimentally measured values to identify the human body parameters. Y. Matsumoto\textit{a} and M.J. Griffin\textit{b}\cite{6-7} gave the dynamic parameters of a person in normal standing posture, legs-bent posture and one-leg posture. Zhang, Chen, Xu gave the dynamic parameters of pedestrians\cite{8}. Both the human-structure interaction dynamic model and the human body dynamic parameter identification method are relatively mature, but it is still difficult for engineers to apply in actual engineering. Designers also do not have a clear understanding of how much influence the human-structure interaction has on the dynamic properties of the structure, and whether to consider it or not in the structural design.

In view of the above problems, this paper takes the long-span box beams as the research objects, employs the SMD model and the pedestrian dynamic parameters in the literature\cite{8} to conduct a modal analysis of the human-structure coupling system to study the dynamic properties of the human-structure interaction on the structure and discuss the analysis results in order to achieve the purpose of optimizing the design.

2. Human-structure coupling system based on SMD model

The pedestrian SMD model is used to construct a human-structure coupling system. As shown in Figure 1, $M_0$, $K_0$, $C_0$ and $M_h$, $K_h$, $C_h$ are the modal mass, stiffness and damping of the structure and the pedestrian, respectively. According to the principle of structural dynamics, the free vibration equation of the human-structure coupling system is:

$$\left[ \begin{array}{c} \dot{x} \\ \ddot{x} \end{array} \right] + \left[ \begin{array}{c} C \\ K \end{array} \right] \left[ \begin{array}{c} x \\ \dot{x} \end{array} \right] = 0 \quad (1)$$

Where: $[M] = \begin{bmatrix} M_0 & 0 \\ 0 & M_h \end{bmatrix}$, $[C] = \begin{bmatrix} C_0 + C_h & -C_h \\ -C_h & C_h \end{bmatrix}$, $[K] = \begin{bmatrix} K_0 + K_h & -K_h \\ -K_h & K_h \end{bmatrix}$.

Introducing the structural and human vibration modes $\phi_{sr}$ and $\phi_{hr}$, the eigenvector equation of the free vibration of the human-structure coupling system is:

$$\begin{bmatrix} \lambda^2_r & 0 \\ 0 & \lambda^2_r \end{bmatrix} \begin{bmatrix} M_0 & 0 \\ 0 & M_h \end{bmatrix} + \lambda^2_r \begin{bmatrix} C_0 + C_h & -C_h \\ -C_h & C_h \end{bmatrix} + \begin{bmatrix} K_0 + K_h & -K_h \\ -K_h & K_h \end{bmatrix} \begin{bmatrix} \phi_{sr} \\ \phi_{hr} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

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

$$\det \begin{bmatrix} (M_0 \cdot \lambda^2_r + (C_0 + C_h)\lambda^2_r + K_0 + K_h & -C_h \lambda_r - K_h \\ -C_h \lambda_r - K_h & M_h \cdot \lambda^2_r + C_h \lambda_r + K_h \end{bmatrix} = 0 \quad (3)$$

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:

$$f_r = \frac{1}{2\pi} |\lambda_r| \quad r = 1, 2, \cdots, n \quad (4)$$

$$\zeta_r = -\frac{\text{Re}(\lambda_r)}{|\lambda_r|} \quad r = 1, 2, \cdots, n \quad (5)$$

3. Numerical simulation analysis of human-structure coupling system

In this section, ANSYS finite element software is used to compare and analyze 70 working conditions with 7 different pedestrian crowd densities and ten large-span box beams of different fundamental frequencies. The mass of a single SMD is 70kg, the stiffness is 10050N/m, the damping is 547kg/s\cite{8}, and the human body frequency is 1.803Hz.
The calculated span of the box beams is 30m, and both ends are simply supported. Q345 steel is used. The material parameters are shown in Table 1. The finite element model of the human-structure coupling system is shown in Figure 2, and the box beam’s section is shown in Figure 3. Ten box beams with different fundamental frequencies can be obtained by changing the height of the box beam section. The box beams’ section dimensions are shown in Table 2 where the structural fundamental frequency is $f_0$, and the frequency ratio $\alpha$ is the structural fundamental frequency divided by the human body frequency.

| Material | Density $\rho$ (kg/m$^3$) | Elastic Modulus $E$ (GPa) | Shear Modulus $G$ (GPa) | Poisson Ratio $\mu$ |
|----------|----------------------------|---------------------------|-------------------------|---------------------|
| Q345     | $7.85 \times 10^3$        | 206                       | 81                      | 0.3                 |

As shown in Table 2, the fundamental frequency of the box beams is low, and the human-structure interaction is obvious\cite{8}, the fundamental frequencies of S1-S6 sections are similar to those of the human body, and the fundamental frequencies of S7-S10 sections are about 1.5-2.0 times those of the human body. The influence of human-structure interaction on the dynamic properties of the structure is explored through the change of the frequency ratio $\alpha$. Pedestrian density adopts seven different situations (0.3 p/m$^2$, 0.5 p/m$^2$, 0.7 p/m$^2$, 0.9 p/m$^2$, 1.1 p/m$^2$, 1.3 p/m$^2$, 1.5 p/m$^2$, “p” stands for person), to explore the effect of crowd density on human-structure interaction. First, perform the empty bridge modal analysis on the S1-S10 box beams to obtain the dynamic properties of the empty bridge, and
then perform the modal analysis on each box beam under seven crowd densities to obtain the corresponding dynamic properties of human-structure coupling system. In order to explore the influence of pedestrians on the dynamic properties of the box girder, the frequency change factor $\beta$ is the structural fundamental frequency of bridge with pedestrian influence divided by that of the empty bridge, and the damping ratio change factor $\gamma$ is the structure damping ratio of bridge with pedestrian influence divided by that of the empty bridge.

Table 2. Box beams’ section dimensions and frequency ratio $\alpha$.

| section | H(m) | W(m) | t(m) | $f_\theta$(Hz) | $\alpha$ |
|---------|------|------|------|----------------|--------|
| S1      | 0.4  | 2.0  | 0.05 | 1.492          | 0.827  |
| S2      | 0.45 | 2.0  | 0.05 | 1.692          | 0.937  |
| S3      | 0.5  | 2.0  | 0.05 | 1.889          | 1.046  |
| S4      | 0.55 | 2.0  | 0.05 | 2.079          | 1.153  |
| S5      | 0.6  | 2.0  | 0.05 | 2.270          | 1.259  |
| S6      | 0.65 | 2.0  | 0.05 | 2.459          | 1.364  |
| S7      | 0.7  | 2.0  | 0.05 | 2.646          | 1.467  |
| S8      | 0.8  | 2.0  | 0.05 | 3.012          | 1.671  |
| S9      | 0.9  | 2.0  | 0.05 | 3.369          | 1.869  |
| S10     | 1.0  | 2.0  | 0.05 | 3.719          | 2.063  |

3.1. The influence of human-structure interaction on the fundamental frequency of the structure

Figure 4 and Figure 5 show the value of the frequency change factor $\beta$ under 70 working conditions. It can be concluded that: (1) When the frequency ratio $\alpha$ is less than 1, the human-structure interaction has a greater influence on the fundamental frequency of the structure. With the increase of $\alpha$, human-structure interaction has a reduced effect on the fundamental frequency of the structure. (2) In most cases, human-structure interaction increases the structural fundamental frequency, and the structural fundamental frequency increases as the density of pedestrians increases. Only under cases of $\alpha=1.046$, $\alpha=1.153$, and $\alpha=1.259$, human-structure interaction leads to the reduction of the structural fundamental frequency. But with the increase of $\alpha$, the reduction of structural fundamental frequency caused by human-structure interaction no longer occurs. (3) When $\alpha$ is greater than 1.5, although the human-structure interaction causes a slight increase in the structural fundamental frequency, the increase does not exceed 1%, and the effect is basically negligible.

![Figure 4. Influence of different pedestrian density on S1-S6 box beams’ fundamental frequency.](image)
Figure 5. Influence of different pedestrian density on S7-S10 box beams’ fundamental frequency.

Figure 6. Influence of different pedestrian density on S1-S6 box beams damping ratio.

Figure 7. Influence of different pedestrian density on S7-S10 box beams damping ratio.

3.2. The influence of human-structure interaction on structural damping ratio

Figures 6 and 7 show the value of the damping ratio change factor $\gamma$ under 70 working conditions. It can be concluded that: (1) Human-structure interaction always increases the damping ratio of the structure. (2) When the frequency ratio $\alpha$ is less than 1, the structural damping ratio is greatly affected by pedestrians, but the influence of pedestrian density changes on the damping ratio is not obvious. (3) As the frequency ratio $\alpha$ increases, the increase of structural damping ratio significantly slows down, but the influence of pedestrian density change on the damping ratio increases.
4. Conclusion

For the comparisons of the above 70 working conditions, a total of 10 box beams with different frequencies and 7 different pedestrian densities are used, and the structure-human frequency ratio $\alpha$ is between 0.827 and 2.063. Through the modal analysis of the structure, the influence of human-structure interaction on structural dynamic properties is studied. The main conclusions are as follows:

1. When the frequency ratio $\alpha$ is less than 1, that is, when the fundamental frequency of the structure is less than the frequency of the human body, the human-structure interaction greatly increases the fundamental frequency of the structure. Even in the case of low pedestrian density, the fundamental frequency of the structure will increase to the vicinity of the human body frequency. When $\alpha$ is slightly greater than 1, the human-structure interaction will reduce the fundamental frequency of the structure to near human body frequency. When $\alpha$ is greater than 1.5, the influence of human-structure interaction on the fundamental frequency of the structure can be ignored.

2. Human-structure interaction always increases the damping ratio of the structure, but with the increase of the frequency ratio $\alpha$, the increase of the structure damping ratio obviously slows down. When the frequency ratio $\alpha$ is greater than 2, the increase does not exceed 20%.

3. The human-structure interaction is greatly affected by the frequency ratio $\alpha$. When $\alpha$ is less than or equal to 1.25, the human-structure interaction has a great influence on the dynamic properties of the structure. The human-structure interaction must be considered in the structural design. As the frequency ratio $\alpha$ increases, the influence of the human-structure interaction on the dynamic properties of the structure reduces. When the frequency ratio $\alpha$ is greater than 2, the influence of the human-structure interaction on the dynamic properties of the structure can be ignored in the structural design.

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