Effect of temperature on natural frequencies of bridge structure of metallurgical crane

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Abstract. It is an important prerequisite for structural design and structural health monitoring to accurately obtain the natural frequencies and modal shapes of the structures, however, which are not only related to the stiffness and mass of the system itself but also affected by temperature, humidity, load and other factors. Therefore, the effect of environmental factors on the dynamic parameters of the structures should not be ignored in the process of dynamic analysis, especially for the structures which run in the complex environment such as bridge structures of metallurgical cranes. In this paper, two physical fields of solid heat transfer and solid mechanics in COMSOL are used to analyse the dynamic parameters of the bridge structure of a double-beam bridge crane based on the consideration of temperature effect and neglect of temperature effect respectively. The results show that, without considering the influence of ambient temperature on the material of crane bridge structure, whether the temperature effect is taken into account or not has no obvious effect on the form of structural vibration modal shapes. In addition, it can be concluded that the natural frequencies of each stage of crane -bridge structure increase under the condition of considering the influence of service ambient temperature, and the increase of natural frequencies of each stage also increases with the increase of convection air temperature at the bottom of the lower cover plate of the main beam.

Keywords: Natural frequencies, Temperature, Bridge structure, Metallurgical crane

1. Introduction

A metallurgical Crane refers to a special crane for lifting molten metal, which works by means of the longitudinal movement of the bridge structure along the powerhouse track direction, the lateral movement of the trolley and the lifting movement of the hook. Generally, metallurgical cranes work in the environment, where the temperature is -10°C to +50°C, but the local radiation temperature of the molten metal lifted to the bridge structure and various devices of metallurgical crane is much higher than the environment temperature.

The location and prediction of structural damage based on dynamic testing is a challenging problem in the field of structural health monitoring. In the process, it is very important to obtain the natural frequencies and modal shapes of structures accurately. However, most engineering structures are complex structures composed of multiple materials and substructures, which determines that their dynamic parameters are not only related to the stiffness and mass of the system itself, but also affected
by temperature, humidity, load, wind[1] and other factors. There is no doubt that environmental factors have an adverse effect on the dynamic based structural damage identification. For example, the temperature difference between day and night and the temperature difference between seasons will lead to the change of constraint degree and deflection at both ends of the bridge [2]. In addition, the existing research shows that due to the influence of ambient temperature, the change of natural frequency of bridge may be as high as 10%, which is far more than the change of natural frequency caused by general structural damage [3]. Therefore, the influence of environmental factors, especially the environmental temperature, on the dynamic characteristics of structures cannot be ignored in the process of structural health monitoring and damage identification. At present, more and more scholars have begun to study the influence of ambient temperature on the natural frequencies and modal shapes of various structures. An investigation into the effects of temperature change on modal parameters by analytical and field monitoring was reported by D Y Zhang et al. (2012). They concluded that temperature-induced internal forces affect the modal parameter values to greater extent than temperature-induced modulus of elasticity, and the relationships between temperature and variation of modal parameters are different in the case of uniform and non-uniform temperature distributions [4]. Correlations between measured temperatures (air temperature, surface temperature, mean temperature, and modal frequencies for the slab and beam are comparatively analyzed, and the quantitative models are constructed considering nonuniform temperature distribution by Hanbing Liu et al. (2015) [5]. They selected five temperature variables to construct the multiple linear regression models, and their prediction results reveal that the proposed multiple linear regression models possess favorable accuracy to quantify the temperature effect on modal frequencies considering nonuniform temperature distribution. Mohammad Nejati et al. (2015) studied the effects of fiber orientation and temperature on natural frequencies of a functionally graded beam reinforced with fiber and their results show that different parameters, such as thickness-to-radius ratio, effect of temperature variations, distribution of the angle of the fibers, and different boundary conditions, influenced the beam effect on natural frequencies [6]. Wang Lixin et al. (2016) studied the influence of ambient temperature on frequency monitoring of Huangpu Bridge in the Pearl River, and the correlation between temperature and identified frequency is analyzed through time history curve comparison and linear fitting. Their results show that there is a nonlinear negative correlation between the modal frequency of the bridge and the ambient temperature [7]. SUN Limin et al. (2018) investigated the relationship between the temperature and the modal frequencies of bridges through a series of model experiments using a concrete continuous beam bridge model and a steel cable-stayed bridge model in a controlled-temperature chamber. They found that a change in temperature affects the structural frequencies of the bridge as it alters the elastic modulus of the bridge [8]. Investigation of environment temperature effects on modal frequency of circular arch steel structure was carried out by Liu Zhe et al. (2019). Their results show that temperature affects the modal frequency of structure by changing the mechanical properties and structural state of the structural material [9]. However, there are few researches on the influence factors and rules of modal parameters of special structures, such as cranes, especially metallurgical cranes, whose operating environment temperature is much higher than that of concrete structures, steel structures and other common building structures.

COMSOL Multi-physics is a powerful multi-physical-fields simulation software, which is used to simulate the design, equipment and process of various fields such as engineering, manufacturing and scientific research. Based on the two physical fields of solid mechanics and solid heat transfer in COMSOL Multi-physics, the natural frequency analysis of the structure can be carried out to study the influence of temperature on the modal parameters of metallurgical cranes.

2. Theory

2.1 Finite element modal analysis
Modal analysis is the basis of structural dynamic analysis, which mainly calculates the natural frequency and natural mode shape of the model. For a multiple-degree-of-freedom vibration system,
any motion can be synthesized by its free vibration modes. Finite element modal analysis is the process of establishing and numerically analyzing modal modes [10]. Through the finite element modal analysis, the steps to obtain the natural frequencies and modes of the crane bridge structure are as follows.

Firstly, the element, mass and damping matrix of the main beams and end beams of the crane are calculated by the finite element method. Then, by using the principle of element assembly and considering the stiffness and damping of each connection of the main beams and the end beams, the overall stiffness matrix \([K]\), mass matrix \([M]\) and damping matrix \([C]\) of the crane structure are obtained, from which the motion differential equation of the crane system can be obtained:

\[
[M]\ddot{X} + [C]\dot{X} + [K]X = \{F(t)\}
\]  

(1)

Where \(\dot{X}\), \(\ddot{X}\), \(X\), \(F(t)\) are respectively the acceleration, speed, displacement and exciting force vectors of each degree of freedom of the crane system.

If there is no external force, which means that \(F(t) = 0\), the free vibration equation of the crane system is obtained. When calculating the natural frequency and mode shape of the system, the influence of damping can be ignored. In this case, the motion equation of the undamped free vibration of the crane system is:

\[
[M]\ddot{X} + [K]X = 0
\]  

(2)

The corresponding characteristic equation is:

\[
([K] - \bar{\omega}^2)[M]X = 0
\]  

(3)

In the formula, \(\bar{\omega}\) is the natural frequency of the crane system.

During the process of practical engineering application, the dynamic performance of the structure should be evaluated according to the results of modal analysis. Generally, for structures, it is required that the mode frequency of each stage be far away from the working frequency so as to eliminate excessive vibration and noise. For a specific system, the mode shape and natural frequency of the system depend on the physical parameters of the system, such as the structure mass distribution and geometry, which are the inherent attributes of the system.

2.2 Effect of temperature on modal frequency

There are three ways in which the ambient temperature affects the modal frequency of the structure. Firstly, the change of temperature will cause the deformation of the structure, which will change the original size of the structure. Secondly, the change of temperature will cause the internal force, especially in the statically indeterminate structure, while the tension will increase the rigidity of the structure, and the pressure will reduce the rigidity of the structure. Thirdly, the change of temperature will affect the mechanical properties of structural materials, especially the elastic modulus of materials. For example, the modulus of elasticity of concrete and steel will decrease with the increase of temperature, which will lead to the decrease of structural modal frequency.

The influence of temperature on the modes of different structures is different. For beams with fixed ends, temperature change will only cause internal force without deformation; for beams with free ends, temperature change will only cause deformation without internal force. However, most structures will produce internal force and deformation at the same time under the action of temperature change. Taking simply supported beam as an example, the influence mechanism of temperature on structural modal parameters is discussed [11].

Taking a simply supported beam model with constant section, as shown in Figure 1, \(E, a, I, m, L\) are respectively used to represent the elastic modulus, section area, section moment of inertia uniform, mass and span of the simply supported beam, all of which are constants.
The expression of the nth modal frequency is:

$$f_n = \frac{n^2 \pi}{2L^2} \sqrt{\frac{EI}{m}}$$  \hspace{1cm} (4)

By taking the natural logarithm on both sides of the above formula and then taking differential, the following formula can be obtained.

$$\frac{\delta f_n}{f_n} = \frac{1}{2} \frac{\delta E}{E} - 2 \frac{\delta L}{L} + \frac{1}{2} \frac{\delta L}{L}$$  \hspace{1cm} (5)

In the above formula, $\delta$ represents the increment of corresponding parameters. The first term on the right side of the above formula represents the effect of elastic modulus change on frequency, and the second and third terms represent the effect of deformation on frequency.

Assuming that each parameter changes linearly with the temperature, when the temperature changes $\delta T$, the relative change values of each parameter are respectively:

$$\frac{\delta E}{E} = \theta_E \delta T$$
$$\frac{\delta L}{L} = \theta_L \delta T$$
$$\frac{\delta I}{I} = \theta_I \delta T$$  \hspace{1cm} (6)

In the formula, $\theta_E$ is the rate of change of elastic modulus with temperature, which is an undetermined parameter; $\theta_L = \alpha$ is the linear expansion coefficient of the material; $\theta_I$ is slightly fluctuant according to different sections. Generally, the magnitude of $\theta_I$ is the same as $\alpha^4$, so it can be ignored.

Bringing the relative change value of each parameter into the formula (5), what can be obtained is that:

$$\frac{\delta f_n}{f_n} = \frac{1}{2} (\theta_E - 2\alpha) \delta T$$  \hspace{1cm} (7)

The formula can be used to estimate the modal frequency change of simply supported beam caused by temperature change.

3. Numerical simulation

The calculated crane bridge structure is a box beam, with lateral isolation sheets inside. SolidWorks is used for the overall modeling. The bridge structure model is imported into COMSOL through the interface between SolidWorks and COMSOL for subsequent calculation.

3.1 Model construction

The main parameters of the bridge crane include span of 24m, trolley track width of 3.9m, height of main beam of 2700mm, width of main beam of 1800mm, thickness of upper and lower cover plates of 16 mm, thickness of left and right web plates of 10 mm.
In the dynamic analysis process, because the natural frequency and modal shape of the structure mainly depend on the mass distribution and stiffness, the influence of structural details is not significant. Therefore, in the process of modeling, the characteristics with little influence on natural frequencies were simplified. For example, the bolt connections between the main beams and the end beams were simplified as rigid connections and the splicing plate of the end beams were omitted. In addition, some technological geometric features of the crane in the manufacturing process, such as the parts of the main beam flange plates extending out of the beam ends, the gaps between the main beam webs and the end beam webs used to adjust the span, were properly combined or eliminated in the establishment of the model.

3.2 Physical fields and boundary conditions
In the process of modal analysis without considering temperature, only the physical field of solid mechanics was added to COMSOL. The boundary strip of the solid mechanics field is that the whole crane bridge model was simplified as a simply supported beam, which limited the displacement of two end beam supports in y directions and the displacement of one side support in z direction. In addition, a gravity load as a body load is applied to the whole area.

In the process of modal analysis considering temperature, physical field of solid mechanics and physical field of solid heat transfer are added to COMSOL. The boundary conditions of the physical field of solid mechanics are the same as above. The boundary strip of the temperature field was that in order to simulate the actual working condition of metallurgical crane, the convection hot air was applied on the lower surface of the lower cover plate of the main beam, the air pressure was standard atmospheric pressure, and the air temperature was 373.15K, 473.15K, 573.15K respectively.

3.3 Material properties
The material used in the model was high-strength alloy steel, and its material properties are shown in Table 1.

| Property                      | Value  | Elastic modulus (GPa) | Poisson's ratio (1) | Density (kg/m³) | Thermal conductivity (W/(m·K)) |
|-------------------------------|--------|-----------------------|--------------------|-----------------|------------------------------|
| Heat Capacity at Constant pressure (J/(kg·K)) | 475    | 200                   | 0.3                | 7850            | 44.5                         |

3.4 Modal shapes analysis
Figure 3 shows the modal shapes of the structure without considering the influence of temperature.
When the temperature of the convection air at the bottom of the lower cover plate of the main beams is different, except for the different vibration displacement, the vibration form of each modal shape is basically the same. Therefore, without considering the vibration displacement, the modal shape analysis is carried out under the condition that the temperature of the convection air at the bottom of the lower cover plate of the main beams is 373.15k. Figure 4 shows the modal shapes of the structure considering the temperature effect.
It can be concluded from Fig. 3 and Fig. 4 that whether the temperature effect is taken into account or not has no obvious effect on the form of structural vibration modal shapes, and the vibration forms represented by each stage of modal shapes are respectively:

The first modal shape reflects the translation of the two main beams in the x-o-z plane and the bending to the same side.

The second modal shape reflects the bending of the two main beams to the different side in the x-o-z plane.

The third modal shape and the fourth modal shape reflect the bending of the left main beam and the right main beam in the x-o-z plane respectively.

The fifth modal shape reflects the bending of the two main beams to the same side in the y-o-z plane and the translation in the x-o-z plane.

The sixth modal shape reflects the reverse bending of the two main beams in the x-o-z plane.

3.5 Natural frequencies analysis
Natural frequencies with and without considering the effect of temperature are shown in Table 2.
Table 2. Natural frequencies.

| Working condition                        | Natural frequencies (Hz) |
|------------------------------------------|--------------------------|
| Without considering the effect of       |                          |
| temperature                              | 1st | 2nd | 3rd | 4th | 5th | 6th |
| 5.210                                    | 11.726 | 14.205 | 14.481 | 21.162 | 32.665 |
| Temperature of the convection air        | 373.15K | 5.214 | 11.733 | 14.213 | 14.489 | 21.173 | 32.686 |
| 473.15K                                  | 5.216 | 11.740 | 14.220 | 14.497 | 21.183 | 32.705 |
| 573.15K                                  | 5.219 | 11.747 | 14.228 | 14.505 | 21.194 | 32.726 |

The difference between natural frequencies is used to express the change of natural frequencies, as shown in the following formula:

\[ V_f = f_i - f (i = 373.15K, 473.15K, 573.15K) \]  

Where, \( f_i \) is the natural frequency of the structure when the temperature effect is considered, and \( f \) is the natural frequency of the structure when the temperature effect is not considered.

Change quantity of natural frequencies is shown in Table 3.

Table 3. Change quantity of natural frequencies

| Working condition                        | Change quantity of natural frequencies (Hz) |
|------------------------------------------|--------------------------------------------|
|                                          | 1st | 2nd | 3rd | 4th | 5th | 6th |
| Temperature of the convection air        | 373.15K | 0.004 | 0.007 | 0.008 | 0.007 | 0.011 | 0.021 |
| 473.15K                                  | 0.006 | 0.014 | 0.015 | 0.018 | 0.021 | 0.040 |
| 573.15K                                  | 0.009 | 0.021 | 0.023 | 0.024 | 0.032 | 0.061 |

The trends of Change quantity of natural frequencies are shown in Figure 4.

From table 3 and Figure 5, when not considering the influence of ambient temperature on the material of crane bridge structure, it can be concluded that the natural frequencies of each stage of crane -bridge structure increase under the condition of considering the influence of service ambient temperature, that is, \( V_f > 0 \). At the same time, with the increase of convection air temperature at the bottom of the lower cover plate of the main beam, the increase of natural frequencies of each stage also increases.

4. Conclusion

Considering the effect of environmental factors on the dynamic parameters of the structures, especially for the structures which run in the complex environment such as bridge structures of metallurgical cranes, two physical fields of solid heat transfer and solid mechanics in COMSOL are used to analyse the dynamic parameters of the bridge structure of a double-beam bridge crane based on the consideration of temperature effect and neglect of temperature effect respectively. The results
show that, without considering the influence of ambient temperature on the material of crane bridge structure, whether the temperature effect is taken into account or not has no obvious effect on the form of structural vibration modal shapes. In addition, it can be concluded that the natural frequencies of each stage of crane-bridge structure increase under the condition of considering the influence of service ambient temperature, and the increase of natural frequencies of each stage also increases with the increase of convection air temperature at the bottom of the lower cover plate of the main beam. The results of this paper still need to be further verified with operational modal analysis.

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