Analysis of Coupled Vibration and Swing Characteristics of Bridge Crane

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Abstract. The vibration of the crane bridge structure and the swing of the load will cause fatigue damage to the bridge structure and affect the precise positioning of the load. The moving mass constituted by the load, the crane trolley and the flexible main girder is passed through the multi-body rigid-flexible coupling dynamics system of the bridge, and the virtual prototype of the physical model is established. The influence of the swing Angle of the load on the vibration of the main girder, the influence of the running speed of the crane trolley on the vibration of the main girder and the vertical displacement of the running trolley is simulated and analyzed. The simulation results show that the running speed of the crane car affects the vibration frequency of the bridge structure, and has little effect on the vertical displacement of the crane car. The load swing affects the vibration amplitude of the bridge structure and the vertical displacement of the crane trolley. The vibration of the main beam structure has little effect on load swing.

1. Introduction
For a long time, the design of cranes has mostly transformed dynamic problems into static problems. Although the design efficiency is improved, it cannot accurately reflect the actual working conditions and dynamic performance of the crane. In order to obtain more accurate simulation results, it is necessary to establish a rigid-flexible coupling model of the whole machine that is more in line with the actual situation for simulation [1]. Reference [2] uses the bond graph method to quickly and effectively establish a dynamic model of a complex coupled system, which provides a good solution for complex system modeling. Reference [3] uses a modal flexible body (R-Flex) for simulation. The basic principle is to regard the flexible body as a collection of nodes of a finite element model and express the elasticity of the object in a modal form. Reference [4] established a windmill-bridge coupled dynamic system, analyzed the dynamic response of the two-track train intersection under the excitation of different wind speeds, and reached corresponding conclusions. Reference [5-7] establishes a coupled vibration model and obtains the coupled vibration characteristics. Reference [8-10] used the finite element software ANSYS to analyze the dynamic and static characteristics, and obtained the natural frequency and mode shape of the structure. The above simulation model is a rigid model, ignoring the impact of flexible deformation on the entire system.

In summary, this article uses SolidWorks, Ansys and ADAMS software to establish a rigid-flexible coupling model, and simulates the interaction between the coupled vibration of the trolley and the flexible beam and the swing of the hoisting load. Comparing the data obtained from the simulation with the data that only consider vibration or only consider swing, the interaction characteristics of vibration and lifting swing are obtained. It provides a reference for the lightweight design of the main beam and the path planning based on anti-collision.
2. Establishment of virtual prototype of bridge crane

2.1. Three-dimensional solid modeling and import of bridge crane
In order to ensure the accuracy of the simulation results, the SolidWorks software is used to establish a three-dimensional solid model with equal proportions, as shown in Figure 1. The basic parameters are shown in Table 1.

| Main size (m)             | Part quality (kg) |
|---------------------------|-------------------|
| Lifting height            | 16.5              |
| Span of main beam         | 2                 |
| Lifting trolley wheelbase | 2                 |
| Lifting trolley           | 7497              |
| Single main beam Natural  | 6216              |
| Running cart              | 17940             |

Figure 1. Bridge crane model.

Since the physical model is complicated, and this simulation is mainly for the analysis of the vibration of the bridge structure and the swing of the load, it is necessary to wait for the physical model to simplify and remove the parts that are not related to the simulation results, such as screws, motors, etc. Due to the removal of many parts in the trolley, the trolley needs to be counterweighted to restore the original weight of the trolley. The simplified analysis model is shown in Figure 1 (b). Import the simplified assembly into ADAMS/View to get a virtual prototype mode.

2.2. Rigid-flexible coupling model establishment
When the crane is working, the main beam is deformed due to the pressure of the crane structure and the lifting weight. However, the model imported into ADAMS/View is a rigid body and will not be deformed. This makes the simulation results have a large error compared with the actual situation, and the main beam need to be flexibly processed.

Import the main beam model established by SolidWorks into ANSYS. In ANSYS, the element type and material properties of the main beam model are defined first, then the model is divided into meshes, then the connection points and rigid regions are established, and finally the MNF file, namely the modal neutral file, is generated, as shown in Figure 2. Import the generated modal neutral file into ADAMS to replace the original rigid beam in the virtual prototype. This method does not generate intermediate data, and can ensure the consistency of the main beam data to the greatest extent.

Figure 2. Rigid body flexibility.
The load of the crane operation system is generally connected with the crane trolley through the steel wire rope. In order to make the simulation results closer to the actual results, the steel wire rope should be flexible. For the convenience of calculation and solution, the deformation of wire rope is regarded as linear elastic deformation, so the semi-continuous method is adopted to establish the model of wire rope. The idea of this method is to regard the steel wire rope as a section of small rigid cylinders. During the dynamic analysis, the flexible connection pair -- shaft sleeve force is added between each cylinder. The force model between each two small segments is shown in Figure 2(b).

The calculation of shaft sleeve force is shown in Formula 1.

\[
\begin{bmatrix}
  F_x \\
  F_y \\
  F_z \\
  T_x \\
  T_y \\
  T_z
\end{bmatrix}
= \begin{bmatrix}
  K_{11} & 0 & 0 & 0 & 0 \\
  0 & K_{22} & 0 & 0 & 0 \\
  0 & 0 & K_{33} & 0 & 0 \\
  0 & 0 & 0 & K_{44} & 0 \\
  0 & 0 & 0 & 0 & K_{55} \\
  0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  R_x \\
  R_y \\
  R_z \\
  T_x \\
  T_y \\
  T_z
\end{bmatrix}
+ \begin{bmatrix}
  C_{11} & 0 & 0 & 0 & 0 \\
  0 & C_{22} & 0 & 0 & 0 \\
  0 & 0 & C_{33} & 0 & 0 \\
  0 & 0 & 0 & C_{44} & 0 \\
  0 & 0 & 0 & 0 & C_{55} \\
  0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  V_x \\
  V_y \\
  V_z \\
  C_{4} \\
  C_{5} \\
  C_{6}
\end{bmatrix}
+ \begin{bmatrix}
  F_{x0} \\
  F_{y0} \\
  F_{z0} \\
  T_{x0} \\
  T_{y0} \\
  T_{z0}
\end{bmatrix}
\]  

(1)

Where \( F, T \) are force and moment respectively; \( R, \theta \) and \( V \) are the relative displacement, rotation angle and angular velocity between \( i \) and \( j \) respectively; \( K, C \) are the stiffness coefficient and damping coefficient respectively; the subscripts \( X_0, Y_0, Z_0 \) denote the initial values in the \( X, Y, Z \) directions, respectively.

Import the flexible beam into ADAMS, replace the rigid beam in the model, and add a bushing force between the rigid cylinders that make up the steel wire rope to form a flexible steel wire rope. Create a rigid-flexible coupling model for dynamic simulation.

3. Dynamic modeling and analysis

The multi-body rigid-flexible coupling system of the bridge crane is simplified into the model as shown in Figure 3, and the mathematical model of the lifting system of the bridge crane is established based on the Lagrange principle, that is, the swinging characteristics of the lifting load of the bridge crane are studied by using the two-dimensional model. In Figure 3, \( m_1 \) is the mass of the trolley mechanism; \( m_2 \) is the lifting mass; \( x_0 \) is the coordinate between the trolley and the origin of the fixed coordinate at time \( t \); \( x \) is the swing of lifting weight; \( L \) is the effective length of wire rope; \( f(t) \) is the residual accelerating force of the motor driving force, which is related to the starting and braking mechanism.

The differential equation of the car's motion is as follows:

\[
m_2 \left( \frac{d^2 x}{dt^2} - \frac{d^2 x_0}{dt^2} \right) + \frac{m_2gx}{l} = 0
\]  

(2)
\[ m_i \frac{d^2 x_i}{dt^2} + \frac{m_s g x_i}{l} = f(t) \]  

(3)

The above two equations are established together to obtain:

\[ \frac{d^2 x}{dt^2} + \left(1 + \frac{m_s}{m_i}\right) \frac{g x}{l} = \frac{f(t)}{m_i} \]  

(4)

From the first-stage start (brake) system, we can see that \( f(t) \) can be regarded as constant, that is, \( f(t) = \text{constant } P \), the initial condition is that the swing of the lifting weight is zero and the speed is zero. It can be concluded that the swing amplitude of lifting load when the trolley is running is:

\[ x = \frac{P l}{(m_1 + m_2) g} \left[1 - \cos \omega t\right] \]  

(5)

In fact, in the process of swinging, the swing Angle is smaller than the length of the rope, which can be reduced to \( \sin \theta = \tan \theta = \theta \). Then, the horizontal yaw Angle \( \theta \) generated by the lifting weight is:

\[ \theta(t) = \frac{x}{l} = \frac{P}{(m_1 + m_2) g} \left[1 - \cos \omega t\right] \]  

(6)

4. Simulation and analysis

Based on the model parameters and drawings provided by a bridge crane with a span of 16.5m in a factory, this paper conducts modeling analysis. The simulation was carried out in ADAMS2020 environment.

(a) Different speed                        (b) Whether it vibrates

Figure 4. Load swing.
Figure 4 (a) is the swing displacement of the load on the lifting trolley at different moving speeds. The angular frequency of the load swing has nothing to do with the moving speed of the hoisting trolley, but the moving speed of the hoisting trolley will affect the swing amplitude of the load. This is because there is acceleration during a section of the initial movement of the crane, and the inertial force causes the load to swing. Figure 4 (b) shows the swing displacement of the load under the presence or absence of vibration of the crane. The results show that the vibration of the main beam has very little effect on the swing of the load.

Figure 5 shows the effect of the crane on the vibration of the main girder at different speeds and loads with or without swing. By comparing Figure 5 (c) and (d), it can be concluded that as the operating speed of the crane trolley increases, the vibration frequency of the bridge structure increases. The load swing will change the pulling force of the wire rope, which is equivalent to a change in the mass of the load. Comparing Figure 5 (a) and (c), (b) and (d) changes in the mass of the load will cause the vibration amplitude of the bridge structure to change.

Figure 6. Vertical displacement of trolley.
Figure 6 shows the influence of the lifting trolley on the vertical displacement of the trolley under different speeds and loads with or without swing. By comparing Figure 6 (a) and (c), (b) and (d), it can be concluded that the vertical displacement of the crane trolley is basically not affected by its moving speed. Through (a) and (b), (c) Compared with the results of (d), it can be concluded that the mass of the load will affect the vertical displacement of the crane trolley. When the moving speed of the crane trolley is the same, the displacement change trend of the crane trolley in the vertical direction is consistent.

5. conclusion
This paper establishes the dynamic model of the trolley-bridge structure coupling system, discusses the influence of the crane trolley on the vibration of the bridge structure and the swing of the load at different operating speeds, and the influence of the load swing on the vibration of the bridge structure. From the simulation results, it can be seen that the operating speed of the crane will affect the swing of the load, and at the same time affect the vibration period of the main girder structure, and has little effect on the vertical displacement of the crane. The load swing affects the vibration amplitude of the main beam structure and at the same time affects the vertical displacement of the crane trolley. The vibration of the main beam structure has little effect on the swing of the load. The dynamic model in this paper is more consistent with the simulation results, which proves the rationality of the simulation results.

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