Vibration Analysis of Winding Hoisting System based on ADAMS/Cable

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Abstract. In order to study the lateral vibration characteristics of the vertical wire rope of the winding hoisting system, a virtual prototype model including drum, wire rope, head sheaves and guides is established by ADAMS/Cable module. Dynamic simulation of winding hoisting process is carried out by external solution with ADAMS/Solver simulation control language. The validity of the model is verified with a winding hoisting test-bed, the dynamic behavior of the hoisting system under variable speed conditions is analyzed, and the lateral vibration law and the influence on the longitudinal vibration of the suspension rope under the speed change are obtained.

1. Introduction
In order to realize the exploitation of deep mine resources, the demand of ultra-deep hoisting equipment is increasing. For sake of effective development and utilization of deep resources, it is necessary to break through the basic theory and technical restriction of the design, manufacture and operation of existing mine hoisting equipment, and face the scientific challenges [1,2] brought by ultra-deep shaft, heavy load, high safety and so on. For deep mine shaft, winding hoisting systems have a wide application prospect, so the study of the dynamics of winding hoisting systems has significance for the construction and maintenance of subsequent deep shaft hoisting system [3]. This paper employs a virtual prototype to investigate the vibration characteristics.

2. Winding hoisting system modelling

2.1. Flexible wire rope modelling
As the main flexible element, the hoisting wire rope has good flexibility and cross section of non-standard circular shape [4]. Parameter setting of its stiffness and damping, as well as the contact stiffness directly affects the smoothness of the simulation, which often becomes a difficult point. When ADAMS is used for wire rope modelling [5-6], the following ways can be taken.
2.1.1. Modelling with modal neutral files. Wire rope modelling can be done by flexible element generation, which can be divided into two ways: one is to discretize the parts into multiple grids through finite element analysis software, and then use the modal calculation method to build an MNF modal neutral file, and import it into ADAMS to establish the model. Its accuracy is high, but the simulation takes too much time. The second way is direct generation of the MNF file in ADAMS, which can effectively save the simulation time, but the meshing is difficult to control.

2.1.2. Modelling by axle sleeve force method. Through the sleeve force, multiple small cylinders are connected in series to simulate a flexible wire rope. Relative to the length of the overall wire rope, the height of the small cylinder is extremely small, and the wire rope can be regarded as a continuum. Each small cylinder connected in series is a rigid body and doesn’t deform. In order to effectively simulate the vibration characteristics of the wire rope, it is necessary to set the stiffness and damping between the small cylinders to ensure that the series cylinders can undergo mechanical changes such as stretching and bending deformation. This method has higher simulation accuracy and takes less time, but the modelling process is more complicated.

2.1.3. Modelling by rotating pair method. The small cylinders are connected with a rotating pair to simulate a flexible wire rope. Due to the limitation of the degree of freedom of the rotating pair, this method is often used when the torsional deformation of the wire rope is not considered.

2.1.4. Modelling with cable module. The Cable module in the ADAMS is encapsulated with a macro command program for wire rope modeling, the modeling process is designed in a flow-based interface, and the physical parameters are directly assigned. Relatively speaking, the modeling difficulty is relatively less, the simulation time is shorter, and the various mechanical properties and convergence of the wire rope can be simulated to a higher degree. Through comprehensive comparison of these four modeling methods, the Cable module method is employed.

![Figure 1. Dynamic analysis process of winding hoisting experiment system.](image)
2.2. Modelling process for winding hoisting experiment system

2.2.1. Model import. In this paper, the winding hoist system test bed uses a cylindrical spiral drum. Compared with the actual working conditions, the entire hoisting stroke and hoisting speed are relatively small. Therefore, the ADAMS model ignores the winding excitation, and the spiral drum is simplified to a single circular grooved drum to reduce the guiding time during the simulation of wire rope winding drum. The model of the drum and the rigid guide is established in Solidworks and saved as x_t files, which is then imported into the ADAMS software. The material properties, position, name and appearance of each component are set and adjusted [7].

2.2.2. Add constraints. Dynamic vibration analysis of the winding experiment system is done by ADAMS Software. When establishing the corresponding virtual prototype, it is necessary to impose the corresponding motion pair in the prototype model to limit or restrict the mutual movement of the components in the system to maintain the static or dynamic equilibrium state of the entire hoisting system. In ADAMS, the motion pairs contain three types [8]. After importing the virtual prototype, the movement relationship between components needs to be reset.

2.2.3. Add drive and force. There are two ways to add drive to the components in the ADAMS software. The first one is to add a rotary drive or a sliding drive to the motion pair. The other way is adding a drive between two points of two parts. Because the hydraulic drive and power transmission part are ignored in the virtual prototype model, the rotating drive can be applied directly to the drum.

The force produced by the winding process of wire rope is the contact force, which originates from the contact deformation of the two parts, and the amount of deformation is related to the speed. The calculation methods of contact force in ADAMS are mainly divided into compensation method and impact function method. In order to facilitate the determination of contact parameters, the impact function method is used to determine the contact force. Its generalized form can be expressed as equation (1).

\[ F_{nl} = K \delta^e_i + CV_i \]  \hspace{1cm} (1)

where \( F_{nl} \) is the normal contact force, \( K \) is the stiffness of the contact surface of the two parts. For the collision of the rotating body, the stiffness coefficient can be expressed equation (2).

\[ K = \frac{4}{3} R^{1/2} E^* \]  \hspace{1cm} (2)

\[ \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}, \]  \hspace{1cm} \text{where} \ R_1 \text{ is the radius of the wire rope, } R_2 \text{ is the drum radius.}

\[ \frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}, \]  \hspace{1cm} \text{\( v_1 \) is the Poisson’s ratio of the wire rope, } \text{\( v_2 \) is the Poisson’s ratio of the drum liner.}\ E_1 \text{ is the elastic modulus of the wire rope, } E_2 \text{ is the elastic modulus of the drum liner.} \ \delta_i \text{ is the normal penetration depth of the contact point.}\]

The input in the contact definition interface is the penetration depth when the damping reaches its maximum value. After the two objects are in contact, the damping quickly reaches the maximum value and remains unchanged during the contact. Therefore, the penetration depth can be small. Considering the numerical convergence in ADAMS, the recommended value of 0.1mm is generally used.

3. Model validation

Through theoretical modelling, the vibration equations of the string and vertical rope in the coupled horizontal and vertical vibration state are derived. This section mainly relies on the experimental platform of the multi-rope winding hoisting system to measure the lateral vibration characteristics of the vertical rope, as shown in figure 2. Parameters of this platform are listed in Table 1. Experimental measurement results are compared with the theoretical model established above, so the effectiveness of the theoretical model can then be tested.
Table 1. Main hoisting parameters of the multi-rope winding hoisting experimental platform

| Parameters                      | Value       |
|---------------------------------|-------------|
| Empty mass of conveyance $m_1$  | 296 kg      |
| Mass of loaded conveyance $m_2$ | 426 kg      |
| Density of wire rope $p$        | 0.14 kg/m   |
| Elastic Modulus $E$             | $1.03 \times 10^{11}$ Pa |
| Diameter of wire rope $d$       | 6 mm        |
| Damping coefficient $c$         | 300 N/(m/s) |
| Stiffness coefficient $k$       | $3 \times 10^5$ N/m |
| Hoisting height $l$             | 12 m        |
| String length $L$               | 3.2 m       |

Figure 3. Lateral vibration acceleration of the wire rope

(a) Experimental result (b) Theoretical simulation result

Figure 3 (a) shows the measured horizontal acceleration of the steel wire rope at a distance of 300mm from the conveyance, with an amplitude of 6.21 m/s². Figure 3 shows the lateral acceleration obtained from the ADAMS virtual prototype model, with an amplitude of 6.69 m/s². The comparison shows that the maximum simulation amplitude accuracy rate is 92.3%, and overall, the numerical range and change law obtained by the virtual machine model are highly similar to the experiment. Therefore, this model is feasible.
4. Simulation Analysis

4.1. Lateral vibration acceleration of wire rope at different speeds

Figure 4 shows the trend of lateral vibration acceleration when the speed is 0.3 m/s, 0.6 m/s and 0.9 m/s and the wire rope is fully loaded at the position 1 m away from the hoisting conveyance.

It can be seen from the Figure that when the maximum hoisting speed in the acceleration stage is 0.3 m/s, 0.6 m/s and 0.9 m/s, the range of the acceleration amplitude of the lateral vibration of the wire rope is 0-6.96 m/s², 0-3.69 m/s² and 0-7.76 m/s². In the stage of constant speed operation, the range of the acceleration amplitude of the wire rope lateral vibration is 0-12.58 m/s², 0-30.5 m/s² and 0-35.62 m/s². In the deceleration stage, the amplitude range is 0-8.40 m/s², 0-19.37 m/s² and 0-23.25 m/s².

Through comparison among figure 4 (a), figure 4 (b) and figure 4 (c), it can be seen that with the increase of the hoisting speed, the amplitude of the lateral vibration acceleration of the wire rope is increasing. Compared with the hoisting load, the change of speed has a greater impact on the lateral vibration acceleration of the wire rope. In terms of the smoothness of changes in the entire operation process, the speed is more stable when the speed is 0.6 m/s.

4.2. Longitudinal vibration acceleration of the wire rope at different speeds

Figure 5 shows the longitudinal vibration acceleration when the maximum hoisting speed is 0.3 m/s, 0.6 m/s and 0.9 m/s and the wire rope is fully loaded at the position 1 m away from the hoisting conveyance.

It can be seen from the Figure that the longitudinal vibration acceleration of the wire rope during the acceleration phase is relatively stable, and it undergoes a sudden change under the action of tension, but the magnitude of the change is similar, which has little to do with the running speed; The longitudinal vibration acceleration change of the wire rope also randomly appears a maximum or a small value during the uniform speed operation stage. With the increase of the hoisting speed, the extreme value gradually increases and the longitudinal vibration acceleration also changes greatly. As shown in Figure 5 (b), the time point when the speed of change increases corresponds to the time point when the lateral vibration displacement increases. It can be seen that the longitudinal vibration is obviously affected by the lateral vibration, which increases the longitudinal vibration amplitude and causes more extremums, affecting the smoothness of operation.
5. Conclusion
A model of the winding hoisting experiment system is established based on ADAMS/Cable module, and the effectiveness of the model is verified through experiments. The vibration characteristics of the winding hoisting experimental system under variable speed conditions are analyzed. The acceleration of lateral displacement and longitudinal vibration increases significantly with the running speed, and due to the existence of lateral vibration, more extremums of longitudinal vibration acceleration appear and affect the service life of the wire rope.

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