Analysis of the influence on the hydraulic lifting circuit of the boom crane when the characteristics of the steel wire rope changes

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Abstract. In the process of lifting and landing of large hydraulic crane fully loaded, the working condition conversion makes the stress of steel wire rope change frequently and generate additional dynamic load, which makes the movement of the crane unstable and affects the working stability of the hydraulic system, and also leads to the fatigue damage of the tower structure and reduces the effective working life of the tower crane. In order to find the optimal dynamic characteristics of hydraulic system, the initial tension force, stiffness of hoisting wire rope and rigidity of variable amplitude wire rope of hoisting wire rope are studied respectively by means of machine-liquid integration simulation based on the AMESim, a kind of simulation software. The lifting mechanism of a type of closed hydraulic system is modelled and simulated. The results show that the maximum dynamic load of hoisting mechanism is reduced by 92.6% and the stabilization time is reduced by 49%. The optimized stiffness of hoisting wire rope reduces the dynamic load and peak pressure of hoisting mechanism by 5.2% and 4.3% respectively. The stiffness of the variable amplitude steel wire rope has little effect on the dynamic characteristics of lifting.

1. Introduction

For the lifting mechanism of the full-hydraulic tower crane with heavy-duty and full-power, a large inertial dynamic load will be generated when the operating conditions change, such as acceleration lifting, braking hover, acceleration descent, and deceleration descent. It will not only cause the vibration of the overall structure of the tower but also cause pressure fluctuations in the hydraulic system, so we need to analyze the dynamic characteristics of the lifting mechanism when the working conditions change. In paper [1], the values and curves of various performance parameters of the hoisting system will be obtained by means of integrated modeling and simulation of the machine and fluid. First, the mechanical-hydraulic system model of the hoisting mechanism will be established by using The AMESim, a kind of modeling and simulation software. Then, by analyzing the transmission devices of the hoisting mechanism, it is considered that the steel wire rope (hereinafter referred to as the rope) is the most typical elastic-damping member. The difference in initial tension and rigidity will alleviate the impact of the inertial dynamic load on the system to a certain extent. Therefore, on the basis of the model that has been built, the simulation is carried out under different conditions of the initial tension of the hoisting rope, the rigidity of the hoisting rope and the rigidity of the amplitude-changing rope. By comparing and analyzing the simulation results, the influence of various factors on the dynamic characteristics of the hoisting mechanism is obtained [2, 3].
2. Working principle of the lifting system

The function of the tower crane lifting mechanism is to drive and control the lifting device to complete the vertical lifting, lowering or hovering of the load at a certain speed within the lifting height range. The lifting mechanism of the boom tower crane studied in this paper is mainly composed of working device and hydraulic drive circuit [4]. Among them, the working device includes a steel wire rope, a drum, a pulley block and a hook, and the hydraulic drive circuit is a variable pump-variable motor closed hydraulic system. Figure 1 is a schematic diagram of the lifting mechanism.

3. Establish the mechanical and hydraulic integration model of lifting system

3.1 Modelling the mechanical structure

First of all, use SolidWorks modeling software to build a three-dimensional solid model of the cantilever and balance arm, as shown in figure 2. Taking the hinge point of the cantilever and the balance arm as the coordinate origin, the weight of the cantilever obtained by the "mass attribute" function in SolidWorks is 30365kg, and the coordinate position of the center of gravity is (43.25, 0) [5].

Then, select the six reserved ports physical module in the AMESim mechanical library. Use port 1 as the hinge point connecting the boom and the balance arm, and set the coordinate positions 2, 3, 4, 5, 6 according to the attribute characteristics shown in the three-dimensional model, each position respectively indicates the articulated point which connected the boom with crown block, force fixing pulley, boom lifting point and arm tip pulley, and the lock line position. After that, build a sketch of the hoisting mechanism model. In this example, a double-rate hoisting pulley set is used, so four sets of pulley modules, drum modules, wire rope modules and physical modules are selected in the mechanical library to build a model sketch, the built model is shown in figure 3.
In particular, it is pointed out that the difficulty of wire rope modeling is the setting of its initial parameters, which is also the difficulty and focus of the entire lifting working device modeling. Its initial elongation needs to be set manually and has a great influence on the simulation results. In order to avoid the forced vibration of the wire rope due to the gravity of the boom when we run the simulation, the initial elongation of the luffing rope can be set as follows:

- Fix one end of the luffing rope at the top of the tower, and connect the other end to the boom lifting point. Run the simulation with the initial elongation of the wire rope set to zero;
- Use the elongation of the wire rope in a stable state after oscillation as the initial elongation of the wire rope, reset the parameters and run the simulation again.

Repeat the steps above repeatedly until the satisfactory initial elongation of the rope is obtained [6].

### 3.2 Modelling the hydraulic system

This simulation analysis of the hydraulic system uses a typical closed volume speed control circuit called ‘variable displacement pump-variable displacement motor’ circuit. However, it will cause hydraulic system leakage, increased oil temperature and damage of hydraulic components by high working pressure when a single motor drives a large load torque, so we use two variable pumps to drive four variable motor drives, the system schematic diagram is shown in figure 4.

![Figure 4](image1)

**Figure 4.** Schematic diagram of hydraulic system.

Use pumps, shuttle valves, relief valve variable motors and other components in the AMESim hydraulic library, then refer to the hydraulic schematic shown in figure 3.3 to build a complete model of the hydraulic system, as shown in figure 5.

![Figure 5](image2)

**Figure 5** Simulation model diagram of hydraulic system.
4. Simulation analyse the system with different wire rope characteristics

For large tower cranes, the speed of the lifting mechanism to drive the load will not be very fast, the moving speed of the wire rope is slow, and the damping force generated accounts for a small proportion of the wire rope pulling force [7, 8]. Therefore, it will not be discussed here. Analysis of the dynamic characteristics of the lifting mechanism. Set the working conditions as shown in figure 6, and analyse based on the simulation model established above.

![Variable pump control current and working condition division.](image)

**Figure 6.** Variable pump control current and working condition division.

4.1 Simulation analyse the system when the initial tension of hoisting rope is different.

Two sets of comparative simulation experiments are set up here to verify the influence of the steel wire tension on the dynamic characteristics of the mechanism. Both of the simulation experiments will use the same lifting weight of 10t, a single ratio pulley block, 17-degree boom swing angle and the acceleration of gravity is $g=9.8\,\text{m/s}^2$. The effect of other disturbances is not considered. When the load remains stationary or at a constant speed, the pulling force of a single rope is $F_{r1}=10000\times9.8/2=49\,\text{kN}$. The batch processing function is used to set the initial tension of the steel wire ropes in the two comparison groups to be 0 and 49kN, respectively, then run the simulation.

The curve of the inertial of the hoisting load and the system pressure is shown in figure 7(a) and figure 7(b) under two different initial tensions of the hoisting rope.

![Simulation comparison of different initial tension forces](image)

**Figure 7.** Simulation comparison of different initial tension forces: (a) load inertia load comparison curve; (b) high pressure side pressure curve of hydraulic system.
Table 1 lists the dynamic performance indicators of the hoisting system under different initial tensions, where the adjustment time error band to restore the steady state is taken as ±5%.

**Table 1. Dynamic performance index of lifting system under different initial tension.**

| Working condition       | Initial tension (kN) | Maximum dynamic load (kN) | Maximum overshoot of dynamic load | Peak pressure (MPa) | Maximum overshoot of pressure | Adjustment time (s) |
|-------------------------|----------------------|---------------------------|-----------------------------------|---------------------|-------------------------------|---------------------|
| Lifting from the ground | 0                    | 89.7                      | 91.6%                             | 4.90                | 93.6%                         | 2.05                |
|                         | 52                   | 6.60                      | 6.8%                              | 4.03                | 59.0%                         | 1.04                |
| Secondary lifting       | 0                    | 5.27                      | 5.1%                              | 3.70                | 44.0%                         | 1.02                |
|                         | 52                   | 5.37                      | 5.5%                              | 3.60                | 42.0%                         | 1.03                |

According to the figure 7 and table 1, it is not difficult to find that the control group with the initial tension set to 52kN has a 92.6% reduction in the maximum dynamic load under the lifting condition of the load compared to the control group with the initial tension set to 0. The adjustment time reduced by 49%. In the control group with the initial tension of 52kN, the lifting force acting on the load at the initial moment is equal to the gravity of the load, so in this case, lifting from the ground is equivalent to the second lifting condition. The dynamic load and pressure curve at the high-pressure side while lifting the load from the ground basically consistent with the second lifting condition. The data given in table 1 can also verify this point well. After going through the load off-ground stage, the tension of the steel wire ropes of the two control groups stabilized at the same value. When they experienced other working conditions, the simulation curves of the two basically coincided.

4.2 Simulation Analyse the system when the Stiffness of lifting rope is different.

To investigate the influence of the hoisting rope stiffness on the dynamic characteristics of the hoisting mechanism, five groups of control groups are set up here. Set the initial tension of the hoisting rope is 0, the unit rigidity of the luffing rope is $1.2 \times 10^8$ N/m, and the unit stiffness of the hoisting rope is selected according to the sample, the range is $1.2 \times 10^8$~$2.8 \times 10^8$ N/m. In the batch processing function, the step size of the stiffness change is set to $2 \times 10^7$ N/m and the rest of the settings are the same as above example. Due to the short hoisting time, the length of the hoisting rope changes very little compared to the total length. So the rope length can be regarded as a fixed value, which is 166m in this mechanism. The total stiffness of the lifting wire rope can be calculated from this.

In order to facilitate the observation of the simulation results, only the dynamic load and high-pressure side pressure curves corresponding to the maximum and minimum stiffness are intercepted, as shown in figure 8.

![Figure 8](image_url)

Figure 8. Simulation comparison of different Hoisting wire rope stiffness: (a) load inertia load comparison curve; (b) high pressure side pressure curve of hydraulic system.
The dynamic performance indexes of the hoisting system under different hoisting rope stiffness conditions are listed in Table 2.

Table 2. (a) Dynamic performance index of hoisting system under different stiffness of rope.

| Working condition | Lifting rope stiffness (N/m) | Maximum dynamic load (kN) | Maximum overshoot of dynamic load | Peak pressure (MPa) | Maximum overshoot of pressure | Adjustment time (s) |
|-------------------|-------------------------------|---------------------------|----------------------------------|-------------------|------------------------------|-------------------|
| Lifting from the ground | 722891 | 87.2 | 88.9% | 7.0 | 45.8% | 1.99 |
| | 963855 | 90.6 | 92.4% | 7.1 | 47.7% | 1.79 |
| | 1204819 | 88.3 | 90.1% | 7.2 | 50.0% | 1.43 |
| | 1445783 | 90.5 | 92.3% | 7.3 | 52.0% | 1.12 |
| | 1686747 | 91.8 | 93.7% | 7.3 | 47.9% | 1.68 |

Table 2. (b) Dynamic performance index of hoisting system under different stiffness of rope.

| Working condition | Lifting rope stiffness (N/m) | Maximum load (kN) | Maximum overshoot of dynamic load | Peak pressure (MPa) | Maximum overshoot of pressure | Adjustment time (s) |
|-------------------|-------------------------------|-------------------|----------------------------------|-------------------|------------------------------|-------------------|
| Secondary lifting | 722891 | 5.4 | 5.5% | 5.8 | 20.8% | 1.02 |
| | 963855 | 5.7 | 5.8% | 5.8 | 20.8% | 1.00 |
| | 1204819 | 5.5 | 5.6% | 5.8 | 20.8% | 0.89 |
| | 1445783 | 5.5 | 5.6% | 5.8 | 20.8% | 0.74 |
| | 1686747 | 5.3 | 5.4% | 5.8 | 20.8% | 0.55 |

This shows that when the total stiffness of the hoisting rope changes from 722891N/m to 1686747N/m, the maximum dynamic load is only increased from 87.2kN to 91.8kN, and the peak pressure on the high pressure side is only increased from 7MPa to 7.3MPa, that is, the ratio of the maximum stiffness of the wire rope to the minimum stiffness is 2.33, and the difference between the dynamic load and the peak pressure caused by the two is only 5.2% and 4.3%.

4.3 Simulation Analyse the system when the Stiffness of luffing rope is different.

Also set up five groups of control groups with a lifting weight of 10t, a boom swing angle of 17°, and an initial tension of the hoisting rope of 0. The simulation conditions follow the settings in Figure 4.1. After checking the sample, the variation range of the unit stiffness of the luffing rope is selected as: 8×10⁻⁷~1.2×10⁻⁶N/m, and the simulation step size is set to 10⁻⁷N/m in the AMESim batch processing function. When setting the stiffness of the wire rope in AMESim, the stiffness per unit length needs to be given. According to the equation (1) and (2). It’s not hard to find that the L and k are automatically calculated by the software based on the wire rope tension during the simulation.

\[ F = \frac{EA}{m} \]  \hspace{1cm} (1)

\[ k = \frac{EA}{L} \]  \hspace{1cm} (2)

Since the length change caused by the tensile deformation of the luffing rope is very small compared with the total rope length, both the length of the luffing rope L and the total stiffness k can be regarded as fixed values. The simulation results are shown in figure 9.
The total stiffness which is automatically calculated by the software and some other dynamic performance indexes of five groups different unit stiffness ropes are listed in table 3.

**Table 3.** Dynamic performance index of hoisting system under different stiffness of rope.

| Working condition     | Luffing rope stiffness (N/m) | Maximum dynamic load (kN) | Maximum overshoot of dynamic load (%) | Peak pressure (MPa) | Maximum overshoot of pressure | Adjustment time (s) |
|-----------------------|------------------------------|----------------------------|---------------------------------------|---------------------|------------------------------|---------------------|
| Lifting from the ground | 916163                       | 93.4                       | 95.3%                                 | 6.9                 | 43.8%                        | 2.16                |
|                       | 1051093                      | 90.6                       | 92.4%                                 | 6.9                 | 43.8%                        | 2.16                |
|                       | 1166083                      | 88.9                       | 90.7%                                 | 6.9                 | 43.8%                        | 2.16                |
|                       | 1281086                      | 87.4                       | 89.1%                                 | 6.9                 | 43.8%                        | 2.16                |
| Secondary lifting     | 916163                       | 5.2                        | 5.3%                                  | 5.8                 | 20.8%                        | 1.02                |
|                       | 1051093                      | 5.2                        | 5.3%                                  | 5.8                 | 20.8%                        | 1.02                |
|                       | 1166083                      | 5.3                        | 5.4%                                  | 5.8                 | 20.8%                        | 1.02                |
|                       | 1281086                      | 5.3                        | 5.4%                                  | 5.8                 | 20.8%                        | 1.02                |
|                       | 1396076                      | 5.3                        | 5.4%                                  | 5.8                 | 20.8%                        | 1.02                |

It can be seen that the variation of the stiffness of the luffing rope within the allowable range from 916163 N/m to 1396076 N/m causes very small changes in load inertial load, vertical displacement of the arm tip and pressure on the high-pressure side of the system, which can be ignored. Therefore, the
change of the rigidity of the luffing rope within the allowable range has little effect on the dynamic characteristics of the hoisting. It can be noticed from Figure 9 that the arm tip vibrates up and down around the initial position during the simulation, and the displacement range is between -0.4m~0.6m.

5. Conclusions

It can be clearly seen from the combination of figure 7 and table 1 that setting a certain initial tension is equivalent to transforming the ground-lifting condition into a secondary lifting condition. The simulation results show that when the initial tension is set on the hoisting rope, the dynamic load and high-pressure side pressure oscillations when lifting the load are much smaller than the case when the initial tension is set to zero;

The change in the rigidity of the hoisting wire rope does not significantly improve the dynamic characteristics of the hydraulic system, so when the stiffness of the hoisting wire rope is selected within the specified range, it can be selected with the principle of lowest cost;

The change of the stiffness of the luffing rope within the allowable range has little effect on the lifting dynamic characteristics.

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