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Research on The Influence of Rope Jumping on The Tension of Multi-layer Winding Wire Ropes in Super Deep Mine Hoisting Machine

Tianran Huang^{1,2}, Jianping Tan^{1,2*}, Shaohua Xue^{1,2} and Lixiang Shi^{1,2}

¹College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan, 410083, China

²State Key Laboratory Of High Performance Complex Manufacturing, Central South University, Changsha, Hunan, 410083, China

*Corresponding author's e-mail: 251211024@qq.com

Abstract: Aimed at the process of rope arrangement in double-rope winding drum of super-deep mine hoist, the tension change during rope jumping fault is studied. By analyzing the relationship between the length difference of two ropes caused by rope jumping and tension, the tension simulation model of multi-layer winding drum rope jumping is established in MATLAB, and the results of simulation and experiment are analyzed and compared. The results show that the rope jumping fault will lead to the tension change of the two ropes, and under different rope jumping faults, the tension change law of the rope is different. The simulation model can well reflect the relationship between rope jumping and tension change, and can quantitatively simulate the tension change during rope jumping. These results have important reference value for fault diagnosis research of hoisting system jump in ultra-deep mine.

1. Introduction

In recent years, with the rapid development of China's economy, the demand for various mineral resources is increasing day by day, but the gradual depletion of shallow mineral resources has seriously hindered the improvement of mineral exploitation. Therefore, the mining of underground mineral resources will expand to deep seats, and the mining depth will reach 1000-2000m in the future. Up to this depth, the single-rope winding and multi-rope friction hoist currently used can no longer meet the demand, and multi-rope winding hoist will become the mainstream[1-2].

As shown in Figure 1, the double rope winding hoist uses two wire ropes to lift a cage at the same time. In operation, the tension difference between the two wire ropes may be too large due to the fault of rope arrangement. The rope arrangement fault of hoist refers to the phenomenon of "rope riding" and "rope jumping" which occurs because the wire rope can not be arranged in an orderly manner on the drum, among which rope jumping is more common. The rope groove formed by wire rope winding has little restraint effect at the exit of the rope, and the rope jumping may occur because of the error of wire rope diameter, drum diameter and the vibration of the rope when the hoist is running[3-4].



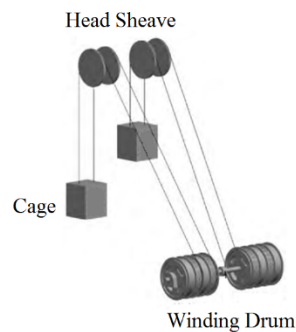


Figure 1. Double rope winding hoist.

For double rope winding hoist, the fault of rope arrangement will cause asynchronization of promotion. Figure 2 is the top view of the drum. When rope jumping occurs, the wire rope crosses directly from one groove to the next groove, as shown in Figure 2 (a). This makes the position of wire rope in the two drums different, which means that the transition between layers of the right drum is prior to that of the left drum, as shown in Figure 2 (b). At this time, because of the different winding radius, the winding length difference produced by winding a circle is very large, resulting in a large difference in tension, which makes a single wire rope bear too much force. Excessive tension will increase abnormal wear and tear of wire rope, which will cause breakage of wire rope [5-6], an equipment failure, casualties and other production accidents.

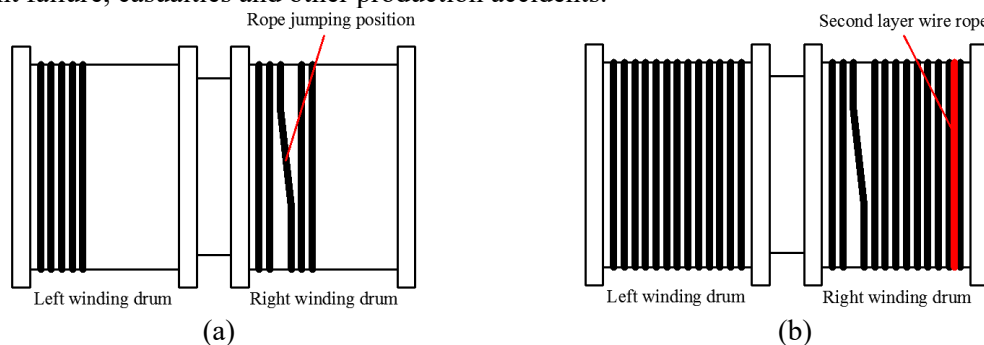


Figure 2. The interlayer transition asynchrony caused by rope jumping.

Therefore, in order to avoid tension instability during the interlayer transition caused by rope jumping, starting from the unbalanced tension phenomenon of rope jumping fault, this paper studies the relationship between rope jumping fault and tension change in the process of rope winding, expecting to establish a rope jumping tension change model to provide basis for rope jumping fault diagnosis."

2. Dynamic modeling of rope jumping

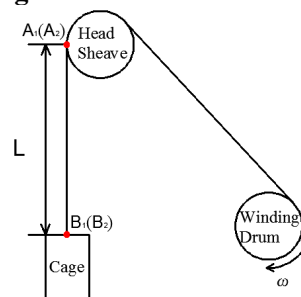


Figure 3. Sketch diagram of the operation of hoist rope.

As shown in Figure 3, the two wire ropes wound on different drums pull the cage through the head sheave and are named as No. 1 and No. 2 wire ropes respectively. The points A1 and A2 are the separation points between the wire rope and the drum, and the points B1 and B2 are the connection

points between the wire rope and the cage. When the cage is in the upward motion state, the differential equation of dynamic tension in the lifting process is [7-9]

$$F'' = \left[ES(g+a) - \left(\frac{3ES}{3M + \rho L} + a \right) F + 2vF' \right] L^{-1} \quad (1)$$

In the formula: F is tension of wire rope at points A_1 and A_2 , E is elastic modulus of wire rope, S is section area of wire rope, a is acceleration of cage movement, M is mass of cage, including container and payload, ρ is mass of wire rope per meter, L is rope length of suspended wire rope, m ; v is running speed of cage.

When rope jumping occurs, the winding radius of the wire rope increases, which makes the acceleration and speed change, thus making the tension change. The running speed of cage is related to the speed and acceleration of wire rope winding, so the acceleration of rope jumping is solved first.

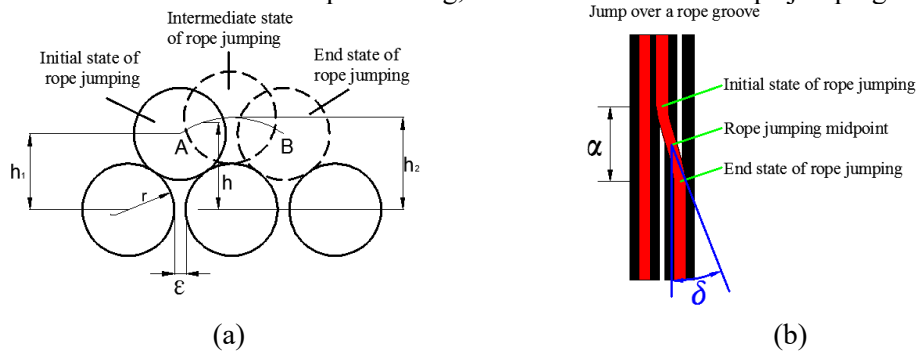


Figure 4. The variation of the winding radius during the rope jumping.

In Figure 4(a) and Figure 4(b), the center angle of the drum corresponding to the rope jumping process is α , the angle between the rope and the rope groove is δ , the maximum value is δ_{\max} . The curve AB is the track of the center of the upper rope, h is the height difference between the upper and lower rope centers, ε is the clearance of the rope groove, and the arrangement of the rope forms central symmetry at the midpoint of the rope jumping. When rope jumping occurs, the winding radius R_{\max} of the wire rope on the drum is as follows

$$R_{\max} = h_2 - h_1 + \frac{R_1}{\cos \delta_{\max}} \quad (2)$$

In order to simplify the model and facilitate calculation, it is considered that R varies linearly with time in the process of rope jumping, reaches the maximum R_{\max} at the midpoint of rope jumping, and t is the time of rope jumping, then the relationship between R and t is as follows

$$\begin{cases} R = \frac{2R_{\max}\omega}{\alpha}t & , \quad 0 < t < \frac{\alpha}{2\omega} \\ R = 2R_{\max} - \frac{2R_{\max}\omega}{\alpha}t & , \quad \frac{\alpha}{2\omega} < t < \frac{\alpha}{\omega} \end{cases} \quad (3)$$

$$h_1 = \left[(2r)^2 - \left(r + \frac{\varepsilon}{2} \right)^2 \right]^{1/2} \quad (4)$$

$$h_2 = 2r \quad (5)$$

Therefore, at time t , the difference of winding length ΔL caused by rope jumping is as follows

$$\Delta L = \int_0^t (R - R_1) \omega dt \quad (6)$$

In the formula: R_1 is the winding radius when the wire rope is in normal arrangement, ω is the angular speed of the drum, r is the radius of the wire rope.

ΔL will make the length of the suspension section of the two wire ropes inconsistent. Because of

the contact slider limitation between the cage and the cage guide, the cage will not deviate. In order to keep the suspension length of the two wire ropes equal, the tension of the wire rope will change, which will make the elongation of the suspension section of the wire rope changed, thus counteracting ΔL . Assuming that rope jumping occurs on No. 2 rope, the tension of No. 2 rope increases, the tension of No. 1 rope decreases, and the elongation changes of No. 1 and No. 2 rope caused by rope jumping are $\Delta L_1 < 0$ and $\Delta L_2 > 0$ respectively, then

$$-\Delta L_1 + \Delta L_2 = \Delta L \quad (7)$$

It is also known that the cage displacement s caused by the change of the elongation of the wire rope at this time is as follows

$$s = -\Delta L_1 \quad (8)$$

The acceleration a of the cage is

$$a = \frac{d^2 s}{dt^2} \quad (9)$$

The force analysis of cage and wire rope is carried out. In this paper, the cage guide is sliding cage guide, and the friction between the cage and the passage is sliding friction, as shown in Figure 5. Assuming that rope jumping occurs on rope No.2, the cage tends to skew counterclockwise, so the force between the channel and cage mainly concentrates on the positions of N_1 and N_2 .

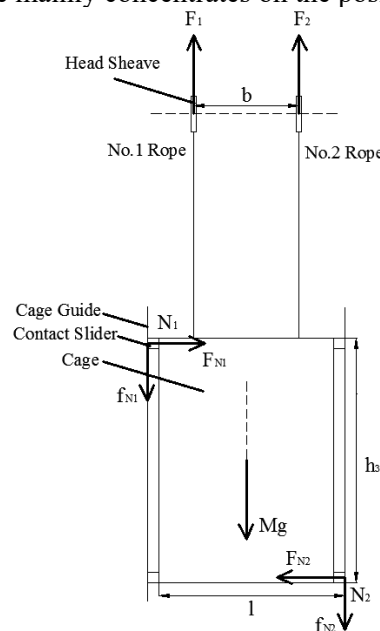


Figure 5. Sketch diagram of force analysis of wire rope and cage in rope jumping. Taking the cage as a whole, its acceleration is a , and its stress state is as follows

$$F_2 + F_1 = (M + \rho L)a + f_{N1} + f_{N2} \quad (10)$$

$$F_2 b + f_{N1} l = F_1 b + F_{N1} h + F_{N2} h + f_{N2} l \quad (11)$$

$$F_{N1} = F_{N2} \quad (12)$$

$$f_{N1} = \mu F_{N2}, \quad f_{N2} = \mu F_{N2} \quad (13)$$

In the formula: b is the distance between the first and second head sheave, h_3 is the height of the cage, l is the width of the cage, f_{N1} and f_{N2} is the friction force between the cage and the channel, F_{N1} and F_{N2} is the pressure between the cage and the channel, and μ is the friction coefficient between the cage and the cage guide.

The relationship between F_1 , F_2 and a can be obtained by formula (10)-(13)

$$F_2(1 - \frac{b\mu}{h}) + F_1(1 + \frac{b\mu}{h}) = (M + \rho L)a \quad (14)$$

Because the rope jumping time is very short, if it is regarded as a variable acceleration process, the calculation will become complicated and the difference of result is very small. Therefore, it is simplified as a uniform acceleration process. In the process of rope jumping, the tension changes of No. 1 and No. 2 wire rope are ΔF_1 and ΔF_2 . they are satisfied respectively

$$\Delta F_2(1 - \frac{b\mu}{h}) + \Delta F_1(1 + \frac{b\mu}{h}) = 0 \quad (15)$$

The elastic modulus of wire rope is obtained by deformation experiment near the working tension. The working tension F is proportional to the deformation Δl

$$\Delta l = \frac{Fl}{ES} \quad (16)$$

When formula (16) is introduced into formula (15), it is obtained that

$$\frac{\Delta L_1}{\Delta L_2} = \left(1 + \frac{b\mu}{h}\right) \cdot \left(\frac{b\mu}{h} - 1\right)^{-1} \quad (17)$$

Formulas(3), (6), (7), (9), (17) show that

$$\begin{cases} a = \left(\frac{b\mu}{2h} + \frac{1}{2}\right) \frac{2R_{\max}\omega}{\alpha} & , \quad 0 < t < \frac{\alpha}{2\omega} \\ a = -\left(\frac{b\mu}{2h} + \frac{1}{2}\right) \frac{2R_{\max}\omega}{\alpha} & , \quad \frac{\alpha}{2\omega} < t < \frac{\alpha}{\omega} \end{cases} \quad (18)$$

Acceleration of cage in rope jumping is obtained by formula (18).

3. Dynamic simulation of rope jumping

Based on the parameters of CITIC Heavy Industry ultra-deep lifting simulated test platform, the test platform uses 4V 39S+5FC wire rope with a diameter of 10mm. After querying the parameters of the test platform and calculating, the relevant parameters are obtained as shown in Table 1 [10-11].

Table 1. The related parameters of test platform.

Parameters	Numerical value
Mass of wire rope per meter m	0.387kg/m
Section area of wire rope S	46.57mm ²
Elastic modulus of wire rope E	100GPa
Radius of the wire rope r	5mm
Clearance of the rope groove ε	0.5mm
Mass of cage M	1000kg
Height of the cage h_3	2000mm
Width of the cage l	1000mm
Winding radius R	410mm
Friction coefficient between the cage and the cage guide μ	0.3
Distance between the first and second head sheave b	600mm

The rope jumping faults of jumping 1, 2 and 3 rope grooves are analyzed, the rope jumping process is observed and the rope arrangement state of the drum is measured. It is found that the corresponding 1 of rope jumping 1, 2 and 3 rope grooves are about 10 degrees, 12 degrees and 15 degrees respectively, and the corresponding center angles are about 35 degrees, 55 degrees and 70 degrees, respectively. The average acceleration of the first half of the rope jumping process is about 0.12m/s², 0.15m/s² and 0.2m/s², respectively. The average acceleration of the second half of the rope jumping process is about - 0.12m/s², - 0.15m/s² and - 0.2m/s². The total duration of the rope jumping process is about 0.24s, 0.35s and 0.5s, respectively. Assuming that rope jumping takes place on 15th second, the

acceleration variation of the hoist during rope jumping is shown in Figure 6.

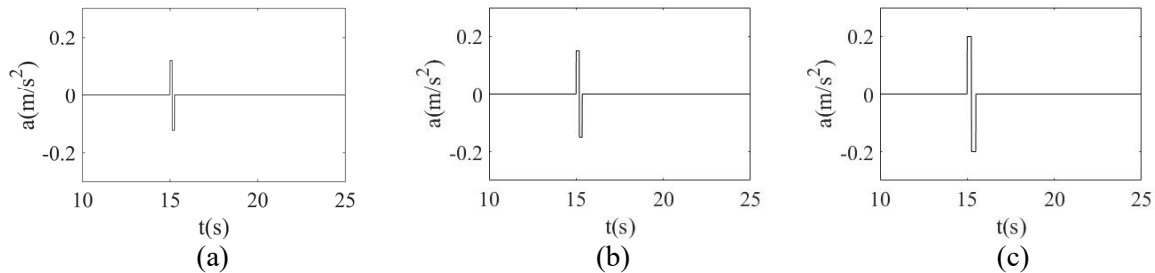


Figure 6. The acceleration of rope jumping in hoisting stage.

According to formulas (1), (18) and combined with table 1 parameters, the Simulink tension simulation model of rope jumping process is established. It is considered that the initial tension of wire rope is set to 4950N, the initial position is set to 0, the distance from the head sheave is 50m, the hoist starts to lift in 0 seconds, the speed is 1.0m/s, and rope jumping happened on fifteenth second.

The numerical method is a variable step calculator and a fourth-order Runge-Kutta algorithm. The simulation time is 30s. The tension curve of the middle 10s-25s smooth running process is selected to analyze, and the tension curve of rope jumping under three conditions of jumping over 1, 2 and 3 rope grooves is obtained as shown in Figure 7.

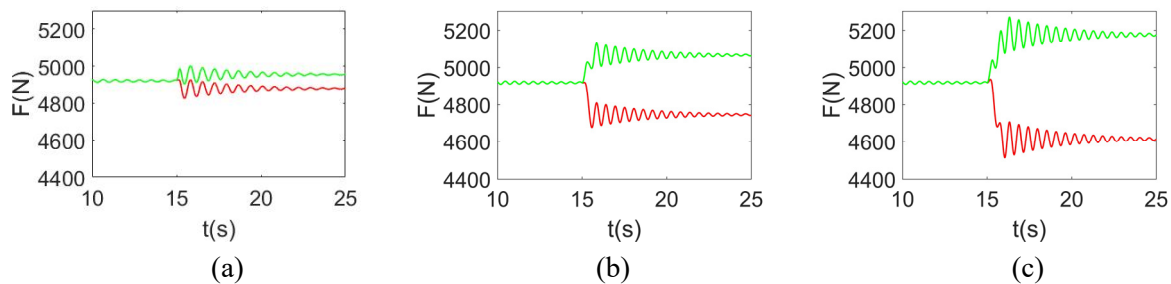


Figure 7. Simulated rope load evolution of rope jumping with time.

As shown in Figure 7(a) -7 (c), the tension of wire rope changes when rope jumping occurs, the tension of rope jumping increases, the tension of another rope decreases, and the more rope grooves jumped, the greater the tension variation range. This is because the greater the difference of rope length caused by rope jumping, the greater the variation of rope elongation caused by rope jumping. The more rope grooves jumped over, the greater the fluctuation of tension. This is because the more rope grooves jumped over, the greater the acceleration caused by rope jumping, the greater the inertial load and impact caused by rope jumping [12-15]. After stabilization, the tension change of single wire rope is about 90N, 150N and 230N, respectively.

4. Wire rope jumping test verification

The arrangement of the winding drum of the lifting test bench for ultra-deep well of CITIC Heavy Industries in Luoyang is shown in Figure 8. Two wire ropes are wound on different drum at the same time. The left side is No. 1 wire rope, and the right side is No. 2 wire rope. Figure 9 shows the normal arrangement of wire ropes.

Measuring the tension of wire rope with pin axis force sensor, which is installed in the axle of the head sheave, as shown in Figure 10. The range of the sensor is 0-5t, and the comprehensive accuracy is $\pm 0.1\%$ FS. The tension of the wire rope during hoisting is collected at a sampling frequency of 60 Hz.



Figure 8. The winding drum of test platform.



Figure 9. The normal rope arrangement of drum.

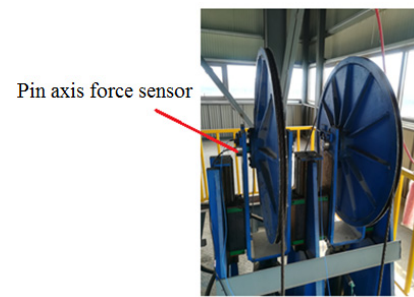


Figure 10. The position of pin axis force sensor.

The total length of the suspended wire rope of the hoist test platform is 46m. the cage is lifted at a speed of 1 m/s. On 15th second, the length of the suspended wire rope is 35 m, which is consistent with the parameters set by the simulation. In the experiment, horizontal force perpendicular to the wire rope is applied at a distance of 0.5m from the rope exit of the drum to make the wire rope jump. The number of rope grooves jumped is changed by changing the tension and the action time. When the whole system is in a static state, there is no obvious change in the data of the tension sensor when the horizontal force is applied, which indicates that the change of tension in the experiment is independent of the tension. Choose No. 2 wire rope on the right side for rope jumping experiment.

When the cage speed is 1 m/s and the number of rope grooves jumped are 1, 2 and 3 respectively, the tension data are compared in the process of 10s-25s. Figure 11 is the experimental result curve. Comparing the tension curves of figures 11 (a), 11(b), 11(c), it can be seen that when rope jumping occurs, the trend of tension change is the same as that of simulation results. When rope jumping 1, 2 and 3 grooves, the tension change of rope is about 80N, 140N and 200N respectively. The more rope grooves jumped, the greater the fluctuation of tension.

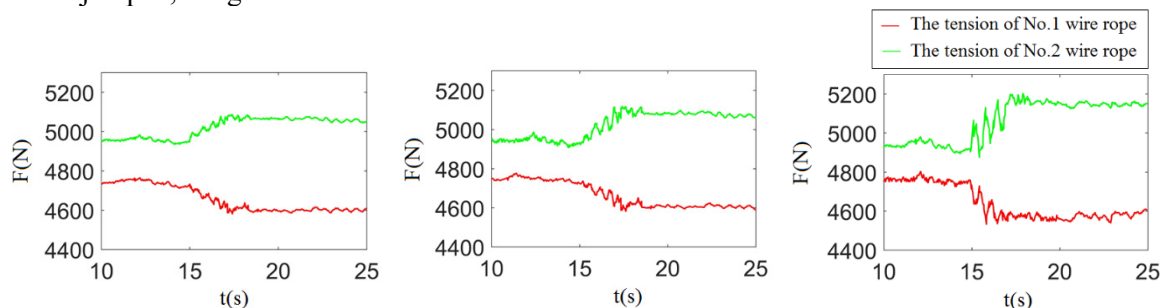


Figure 11. Test rope load evolution of rope jumping with time.

5. Conclusion

(1) In this paper, the process of rope jumping on the drum of double rope winding hoist is analyzed. Combining with the tension equation of the hoist, the tension change model of rope jumping during operation is established, and the tension change curve of rope jumping is obtained.

(2) The wire rope jumping experiment is carried out on the test platform. The experimental results are similar to the simulation results, which proves the validity of the simulation model. The results of simulation and experiment show that the tension of two ropes will change due to the rope jumping fault, and the tension changes are different for different rope jumping processes, which provides a reference for rope jumping fault diagnosis.

(3) The model in this paper neglects the influence of the head sheave, does not consider the wire rope as a fully flexible body, and the experimental and simulation results are not exactly the same, so it is necessary to continue to study and optimize the model in the future.

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