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Research on Matching Safety of Overwind Protection Device

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Abstract: For a long time, in the process of mine hoisting system design, the installation position of overwind and overwind protection device is determined according to experience, which is widely disputed, indicating that the system safety has not reached the perfect state, and the traditional experience conclusion needs to be analyzed theoretically. It is necessary to study the parameter matching problem, analyze the impact of overwind protection devices on the system protection results at different installation positions, and improve the safety of the prompt system from a system perspective. The research about parameters matching of overwinding safety protection system of the shaft multi-rope hoisting system has been worked on in this essay by carrying out simulation analysis with numerical methods, involved with specific examples, in the perspective of the dynamics. According to the research, the braking force on the over wind side is significantly greater than that on the under wind side, there is the best matching relation between overwinding and underwinding braking force, making the braking stroke on the overwinding and underwinding side equal, or the overwinding is slightly larger than the underwinding stroke, which will be more beneficial to the safety of the system. The conclusion of this study is helpful to perfect the theory of overwind protection and improve the security of the system.

Keywords: Over Wind, Under Wind, Protective Devices, Parameter Matching, Mounting Location

1. Introduction

The accident of overwinding is one of accidents that frequently happens in vertical mines hoisting, the system loses control because of some malfunction, other protection become invalid, the moving conveyance fails to stop at the right position, when the moving conveyance runs into the protection area of system, the protection devices of overwinding are supposed to exert braking force on system to stop it in case that the moving conveyance under the mine falls into the bottom or the upside hits the anti-collision beam. With the development of technology, the probability of overwinding accidents is significantly reduced but still exists, so the protective devices of overwinding must be settled as necessary configuration has been wrote into some relative national standard [1-3]. Involving a large number of specific conditions, the duration of overwinding protection is complicated and it keeps updating itself. Two aspects are mainly included, one is the protect device itself, it provides braking force, the other is system design, it ensures the security of protection device for hoisting system from the perspective of system.

For overwinding protective devices, wedgewood cans are wildly used, however, because of its poor reliability, many kinds of protective devices like friction protective device and steel strip protective device comes into used to promote its reliability [4-8].

For system technology, study based on system security is a research hotspot for some time, the team of RW Ottermann [9] has ran experiment on overwinding protect device by establishing a ratio of 1 to 10 model and analyzing the result of simulation, valuable experience of overwinding protect devices and system design were provided by them. Burger [10] analyze the duration of dynamics of over wind and under wind, his opinions on the design of maximum deceleration and maximum deceleration distance is helpful. The concept of system security is put forward by authors of literature [11-16], the reliability of overwinding protection is promoted, but little study on matching safety problem of over wind and under wind protection devices can be found. In this study parameter match and relative installation position of overwinding protection devices were contained.

For mine hoisting system design, most of the install position of overwinding protection device were based on engineers' experience which is wildly controversial, for example, in China, the underwinding protective device of underground installation are generally located 1 meter in advance in the design of coal mines, that is, the underwinding protective device brake the hoisting system in advance. The install location of underwinding device maybe the value of 0.9 ~ 1.3m in advance [17], when the starting point for braking deceleration is greater than or equal to 3g. However, there is still a certain distance between the moving conveyance under the mine and bottom when upside hits the anti-collision beam [18-19]. The accident of Xinji Group company in Anhui province has proved that conclusion comes from traditional experience needs to be analyzed.

In this paper, from the perspective of dynamics, combined with specific example parameters, numerical methods are used to simulate, study the problem of parameter matching, analyze the influence of over-wound protection devices in different installation positions on the result of system protection, and improve the safety of the prompt system from the perspective of the system.

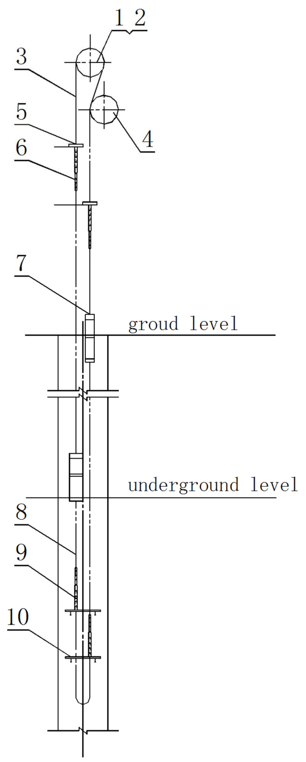

Figure 1. The vertical friction hoisting system (tower hoist system).

1. motor 2. friction wheel 3. head rope 4. hoisting sheave 5. anti-collision beam of the top shaft
6. overwinding protection device of the top shaft 7. hoisting conveyance 8. balance rope
9. underwinding protection device of the bottom shaft 10. anti-collision beam of the bottom shaft.

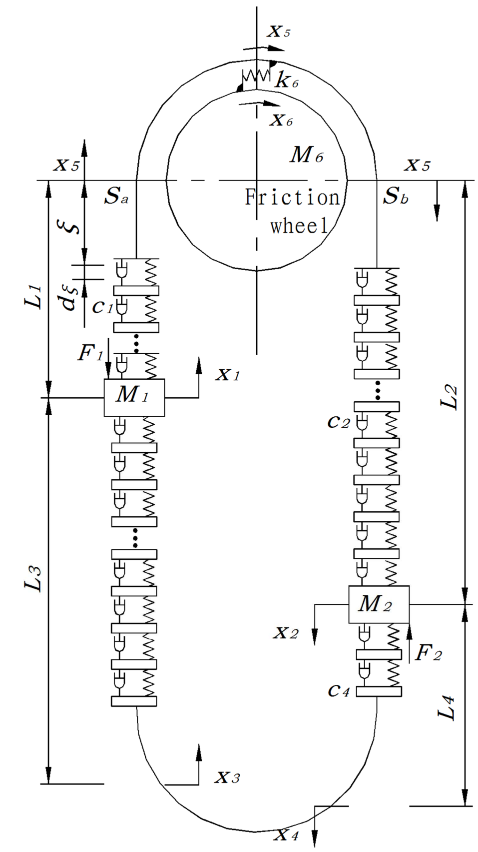

Figure 2. The model of the blackout motor, the no-motion braking system and the non-slip rope.

2. Method

2.1. System Analysis and Modeling

The vertical friction hoisting system (Figure 1) is usually composed of a motor, a friction wheel, a hoisting sheave, head ropes (hoisting cable), hoisting conveyances (skip, cage, etc.), balance ropes, etc.

Considering the precision and convenient of engineering calculations, a discrete multi-degree vertical friction hoisting system dynamic model is developed based on the following assumptions:

1) The influences of the transverse vibration of the wire rope and the hoisting conveyance are ignored.
2) The flexibility of the hoisting foundation is ignored.
3) The hoisting conveyance is taken as the rigid body, that is, the flexibility of the hoisting conveyance, goods, equipment and human body are ignored.
4) Head ropes (the hoisting rope) and the balance ropes are viscoelastic ropes and satisfied with the assumption of the Kelvin model [20]. That is, they are taken as the wire ropes that are uniform mass, flexible, damped, and the flexibility to obey Hooke's law, the viscous damping force obey Newton's law.
5) Balance rope of the upside and downside doesn't disturb each other. For in the transient, the force of the balance rope of the bottom on both sides end is just the gravitation of the arcs, and the effect is slight. The actual

force of the balance ropes is that put on the vertical ground rope when it is raised or down.

6) The model of non-slip rope is considered as a model with six degree of freedom in Figure 2 for analyzation, where the wire rope and friction wheel are connected by a spring (k_6), which is nearly equivalent to a model with five degree of freedom.

For the hoisting system of Figure 1, the dynamic model can be built as shown in the Figure 2.

By using the Lagrange method, a dynamics equation of the system can be given by Eq. (1):

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{x}_i}\right)-\frac{\partial T}{\partial x_i}+\frac{\partial U}{\partial x_i}+\frac{\partial D}{\partial \dot{x}_i}=F_i \quad (i=1,\ 2,\ 3,\ 4,\ 5,\ 6) \tag{1}$$

Where, T, U, D, is the kinetic energy, potential energy and dissipation factor respectively, x_i is the generalized coordinates, x_1~x_6 is the displacement and generalized coordinates of the hoisting side head rope, the lowering side head rope, the hoisting side tail rope, the lowering side tail rope, the steel wire rope at the friction wheel and the friction wheel at the position shown in Figure 2, F_i is the corresponding generalized force.

For the model of Figure 2, a dynamic equation can be given as follows [21]:

$$[M]\{\ddot{x}\}+[D]\{\dot{x}\}+[k]\{x\}=\{F\} \tag{2}$$

Where:

$$M=\begin{bmatrix} M_1+\frac{1}{3}m_{L1}+\frac{1}{3}m_{L2} & 0 & \frac{1}{6}m_{L3} & 0 & \frac{1}{6}m_{L1} & 0 \\ 0 & \frac{1}{3}m_{L2}+\frac{1}{3}m_{L4}+M_2 & 0 & \frac{1}{6}m_{L4} & \frac{1}{6}m_{L2} & 0 \\ \frac{1}{6}m_{L3} & 0 & \frac{1}{3}m_{L3} & 0 & 0 & 0 \\ 0 & \frac{1}{6}m_{L4} & 0 & \frac{1}{3}m_{L4} & 0 & 0 \\ \frac{1}{6}m_{L1} & \frac{1}{6}m_{L2} & 0 & 0 & \frac{1}{3}m_{L1}+\frac{1}{3}m_{L2} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_6 \end{bmatrix}$$

$$C=\begin{bmatrix} c_1+c_3 & 0 & -c_3 & 0 & -c_1 & 0 \\ 0 & c_2+c_4 & 0 & -c_4 & -c_2 & 0 \\ -c_3 & 0 & c_3 & 0 & 0 & 0 \\ 0 & -c_4 & 0 & c_4 & 0 & 0 \\ -c_1 & -c_2 & 0 & 0 & c_1+c_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$K=\begin{bmatrix} k_1+k_3 & 0 & -k_3 & 0 & -k_1 & 0 \\ 0 & k_2+k_4 & 0 & -k_4 & -k_2 & 0 \\ -k_3 & 0 & k_3 & 0 & 0 & 0 \\ 0 & -k_4 & 0 & k_4 & 0 & 0 \\ -k_1 & -k_2 & 0 & 0 & k_1+k_2+k_6 & -k_6 \\ 0 & 0 & 0 & 0 & -k_6 & k_6 \end{bmatrix}$$

$$F=\begin{bmatrix} -F_1+k_1f_1-k_3f_3-(M_1+\frac{1}{2}m_{L1}+\frac{1}{2}m_{L3})g \\ -F_2-k_2f_2+k_4f_4+(M_2+\frac{1}{2}m_{L2}+\frac{1}{2}m_{L4})g \\ k_3f_3-\frac{1}{2}m_{L3}g \\ -k_4f_4+\frac{1}{2}m_{L4}g \\ k_1f_1+k_2f_2-\frac{1}{2}m_{L1}g+\frac{1}{2}m_{L2}g \\ 0 \end{bmatrix}$$

Where in all the above equations:

L_1 - L_4: the length of each wire rope in Figure 2, m;

x_1 - x_5: the generalized coordinates of points as shown in Figure 2;

ρ: the mass of wire rope per unit length, kg / m;

m_{L1} -m_{L4}: the total mass of wire ropes corresponding to L_1 ~ L_4 segment, kg;

M_1: the total mass of the upside hoisting conveyance and load, kg;

M_2: the total mass of the downside hoisting conveyance and load, kg;

M_6: the mass of the friction wheel and motor (including the wire rope contact with the friction wheel), kg;

F_1: the resistance on the upside hoisting conveyance, N;

F_2: the resistance on the downside hoisting conveyance, N.

2.2. Numerical Solution of Dynamic Model

The moving position equation of the hoist varies with the mass matrix [M], damp matrix [C], stiffness matrix [K] as shown in eq. (2). So eq. (2) is a second order ordinary differential equation of coupling, variable coefficient and non-linearity. The period of the system motion is discrete to the number of m intervals, $\Delta t_j=t_j-t_{j-1}$ (j=1, 2,…, m) in each interval, all the matrixes in the equation are supposed as constants, if the dynamical parameters have been known, the mass matrix [M], damp matrix [C], stiffness matrix [K] in the interval are certain, which can be the calculation basis of the next interval, then the differential equations of motion can be written and the original differential equation with variable coefficients can be translated into a differential equation with constant coefficients in the j interval (Δt_j), the system differential equations of motion is:

$$[M]_j\{\ddot{x}\}_j + [C]_j\{\dot{x}\}_j + [k]_j\{x\}_j = \{F\}_j \tag{3}$$

Where: $[M]_j$, $[C]_j$, $[k]_j$ are constant matrixes in the equation, base on the value in the previous interval, and different matrix values are required in each interval. Then the numerical solution of the whole movement process can be calculated by using the iterative algorithm.

3. Result

Simultaneously, the following assumptions are made: The hoist has entered the overwinding area of the full speed v_0=10m/s and the moment when the hoist enters the initial point of the under-winding area is the initial time 0. At the initial time, the system (including hoisting conveyance) has free motion with no acceleration and vibration. The system parameters are given as follows: $L_1=L_4$=30m, $L_2=L_3$=660m, ρ=3.214kg/m, M_1=14000kg, M_2=24000kg, M_6=20000kg.

The steel strip protective device is chose after determining the selection and installation location (the under wind side located 1 meter ahead of the over wind side), there is a certain relationship between the braking forces provided by overwinding and underwinding. Under the initial stress state, the force gradually increases until it reaches a certain value. After the device hits the anti-collision beam, the force applied to the device is much larger than before, equations of over wind and under wind braking force can be given as:

$$\begin{cases} F_u = 0 & (0 < x_1 < 1\text{m}) \\ F_u = (x_1 - 1)\times F_1 & (1 < x_1 < 2\text{m}) \\ F_u = F_1 & (2 < x_1 < 6\text{m}) \\ F_u = 5\times 10^6 & (6\text{m} < x_1, \quad \text{State of impact anti-collision beam}) \end{cases} \tag{4}$$

$$\begin{cases} F_D = (x_2 - 1)\times F_2 & (0 < x_2 < 1\text{m}) \\ F_D = F_2 & (1 < x_2 < 5\text{m}) \\ F_D = 8\times 10^6 & (5\text{m} < x_2, \text{State of impact anti-collision beam}) \end{cases} \tag{5}$$

In the equation set above, F_1 *and* F_2 stands for the maximum braking force (before the device hits the anti-collision beam) on the over wind side and under wind side respectively. By the use of Matlab, the result of system simulation is given as follows:

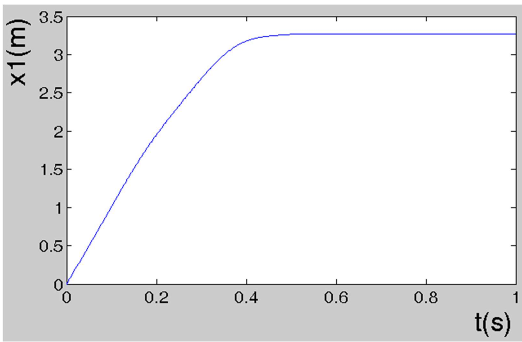

Figure 3. *The movement of hoisting conveyance of over wind.*

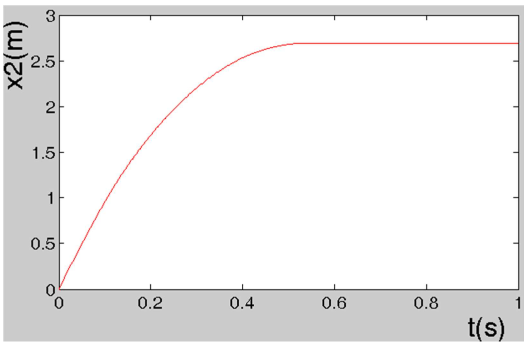

Figure 4. *The movement of hoisting conveyance of under wind.*

It can be figured out from Figure 3 and Figure 4 that both side of hoisting conveyance, powered by overwinding and under-winding protection device, stop moving after 3.25m and 2.7m (the moving distance doesn't change any more) which shows that the protection device does work, it protects the anti-collision beam from being crashed by the hoisting conveyance.

4. Discussion

4.1. Matching the Braking Force Between Overwinding and Underwinding

The braking force set in the overwinding protection device is expected to not only absorbs all of system kinetic energy which meets the related regulation of maximum deceleration, but also avoids failing to set them balanced which cause a certain distance still left between the moving conveyance under the mine and bottom while upside has already hit the anti-collision beam. Then match with light and heavy cages respectively and preset different side of braking force for simulation with the help of Matlab. In the duration of simulation, the side of under wind starts braking 1m ahead (ξ=1m). In the following charts, X_1 stands for the distance between over wind side and initial point while X_2 stands for under wind side, when X_1 is greater than 6m it means the hoisting conveyance hits the anti-collision beam upside, when X_2 is greater than 5m it means the hoisting conveyance hits the anti-collision beam in the bottom.

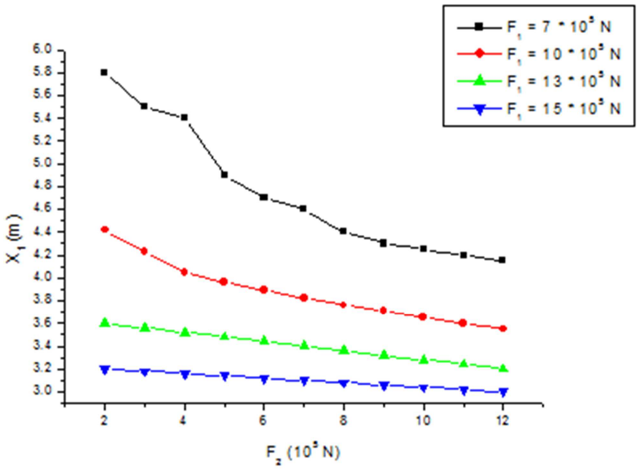

Figure 5. *The curve of the maximum distance of overwinding and underwinding varies along with the distance with the change of F_2, when M_1 is light load, M_2 is heavy load.*

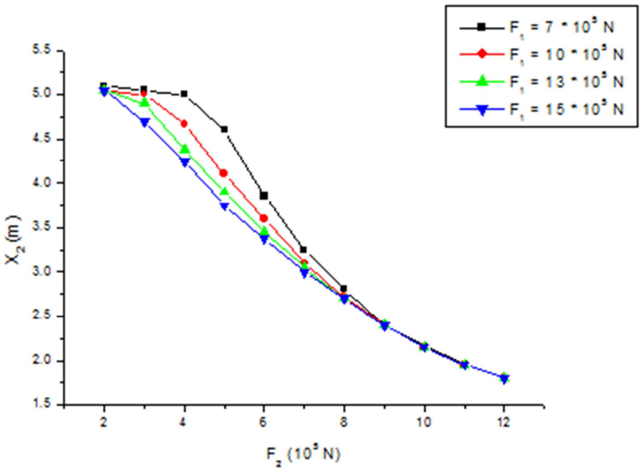

Figure 6. *The curve of the maximum distance of overwinding and underwind varies along with the distance with the change of F_2, when M_1 is light load, M_2 is heavy load.*

Curves of change of X_1,X_2 with F_2 set value (7×10^5, 10×10^5, 13×10^5, 15×10^5) were showed in Figure 5 and Figure 6, when M_1 is light load, M_2 is heavy load and no motor-driven brakes under full-speed over-acceleration. The larger F_1 set, the smaller X_1 will be, while F_2 has little effect on X_1 but has significantly influence on X_2, which means the braking stroke of over wind and under wind side is mainly depend on its braking force preset by protection device.

The conclusion from Figure 7 to Figure 10 is consistent with the above. F_1 is greater than F_2 when X_1 equals to X_2, it means that the over wind side takes over more kinetic energy for a system which is contrary to traditional experience, the over wind side takes over less kinetic energy for the system.

It can be figured out from Figure 5 to Figure 10 that there is the best matching relation between overwinding and underwinding braking force, making the braking stroke on the overwinding and underwinding side equal, or the overwinding is slightly larger than the underwinding stroke.

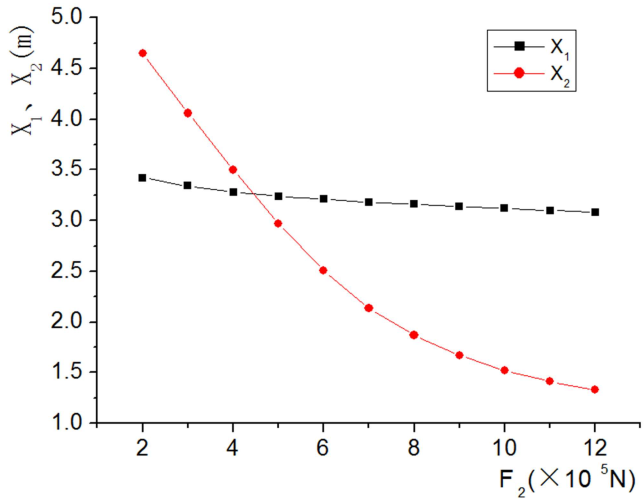

Figure 7. *The curve of the maximum distance of overwinding and underwinding varies along with the distance with the change of F_2, when M_1 is light load, M_2 is light load and F_1=13×10^5 N.*

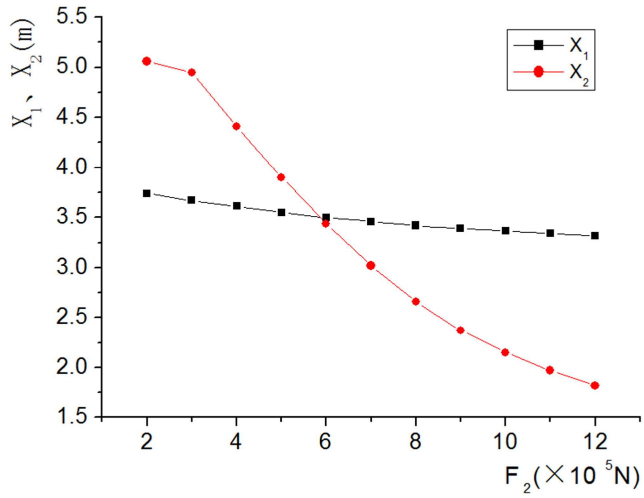

Figure 8. *The curve of the maximum distance of overwinding and underwinding varies along with the distance with the change of F_2, when M_1 is heavy load, M_2 is light load and F_1=13×10^5 N.*

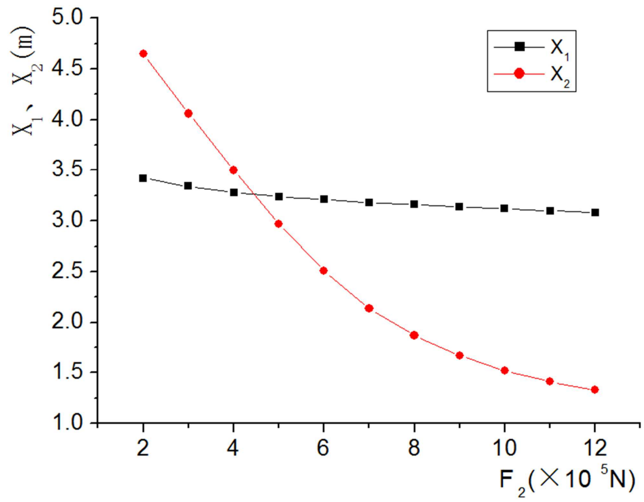

Figure 9. *The curve of the maximum distance of overwinding and underwinding varies along with the distance with the change of F_2, when M_1 is heavy load, M_2 is heavy load and F_1=13×10^5 N.*

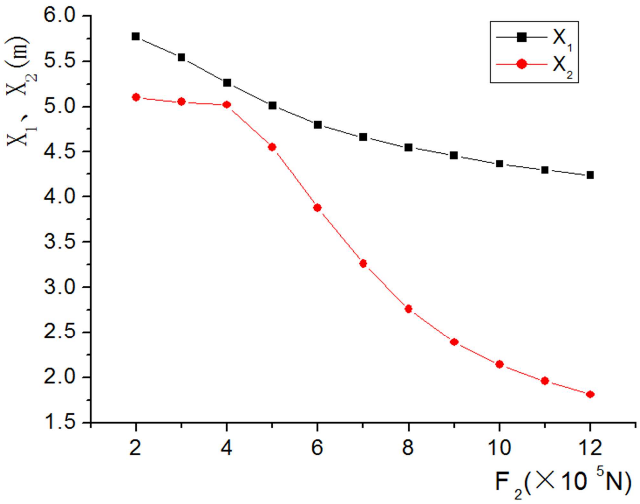

Figure 10. *The curve of the maximum distance of overwinding and underwinding varies along with the distance with the change of F_2, when M_1 is heavy load, M_2 is light load and $F_1=7\times10^5$ N.*

It can also be seen from the above figures that in order to ensure that the braking distance between the upper and lower wells are approximately the same under various accident conditions, that is to say the equalization wells braking distance up and down, F_1 needs to be significantly larger than F_2. This is because F_2 is mainly responsible for absorbing the kinetic energy of the over wind side hoisting conveyance, and F_1 needs to be bear the absorption of the overwinding side hoisting conveyance, hoisting machine, wire rope kinetic energy and other resistance. This conclusion is exactly the opposite of the traditional design which agrees with that the over wind side takes over less kinetic energy for system [17]. It is related to the GB50384-2016 "Coal Industry Shaft and Shaft Design Specification"[17], which states that "... the upside braking device should be supposed to not only absorb and ascend to lift the hoisting conveyance at full speed. In addition to the kinetic energy, the work done by the huge traction of the hoist is also to be overcome, while the down side braking device only absorbs the kinetic energy of the full speed falling conveyance.", basically close to it. Combined with the maximum deceleration and over-roll distance requirements, the reasonable value that can be used in this case is F_1=10~13×10^5 N, F_2=5~8×10^{5}N.

4.2. The Relative Installation Positions of the Overwinding and Underwinding Protection Device

For the decades experience of design of coal industry in China, it is common that apply braking force in advance with under wind side to lose the first weight of under wind side and improve the braking effect. Adjust the distance of overwinding and underwind varies along with the distance in advanced Δx and make the simulated values X_1 and X_2 into Figure 11 and Figure 12 shows the curve when M_1 is in the state of heavy load and M_2 is empty-load. The braking distance X_2 is decreased as the increase of the distance in advanced Δx, it is beneficial to the slowdowns of the whole hoist because of the tension difference. However, it is not the biggest endanger condition and only the state in Figure 11 is taken into account. As shown in Figure 11, the braking distance of the overwinding side X_1 reduces with the increases of the distance in advance, but X_2 increases. For the under-winding side of the hoisting conveyance is braked in advance, the tensile force of the head rope release and part of the kinetic energy are absorbed by the under-winding protective device. Although the overwinding side protective device has lightened some load, the total kinetic energy that both sides protective device absorbed is increased. The increased part is the potential energy of the tensile force released by the head rope of the wire rope under-wind side. Generally speaking, the load of the energy that the protective device absorb isn't relieved, but increased. Therefore, analyze theoretically, the under-wind side is not reasonable to enter the braking protection in advance. Similarly, if the overwinding side enters the braking protection in advance, the tensile force of the wire rope and the vibration will also increase. So it is not advisable. The most reasonable method is the overwinding and under-wind protection enters the up and down the shaft simultaneously.

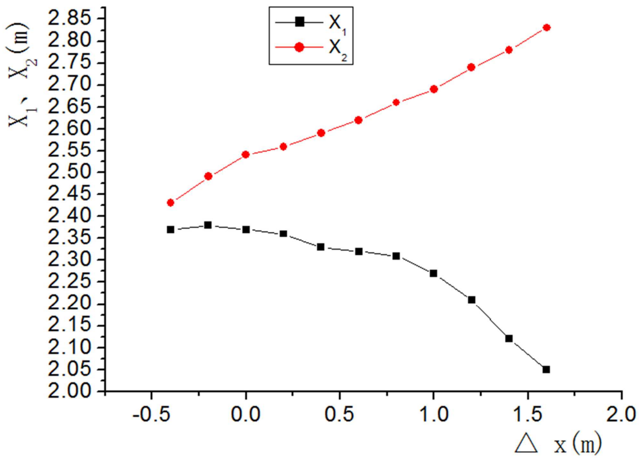

Figure 11. *The curve of the maximum distance of overwinding and underwind varies along with the distance in advanced Δx, when M_1 is light load, M_2 is heavy load and $F_1=13\times10^5$ N.*

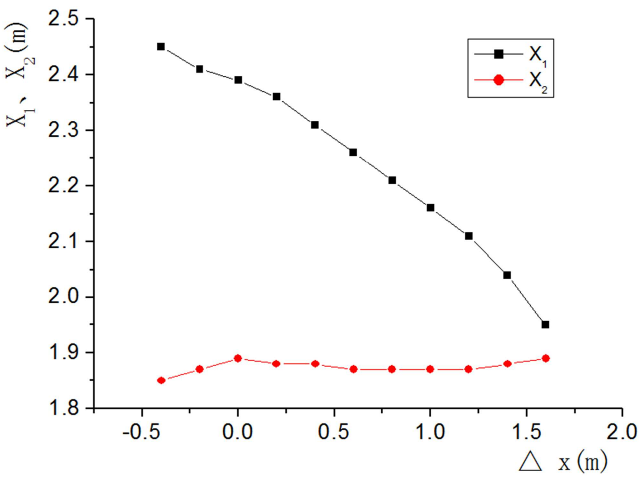

Figure 12. *The curve of the maximum distance of overwinding and underwind varies along with the distance in advanced Δx, when M_1 is heavy load, M_2 is light load and $F_1=13\times10^5$ N.*

From the perspective of design factors, the relative position relationship of the over wind protection device in this case is: the position of the over wind and under wind is not ahead of each other, that is, the over wind and under wind protection of the well is performed at the same time; Or the over wind protection device is a small amount of overwinding protection devices are in advance of the under wind protection device.

5. Conclusion

To sum up, a reliable overwinding protection device is not enough to ensure the reliability of the over wind protection of hoisting system, system security is required as guarantee. First of all, the braking force parameters of over wind protection device should be matched to avoid the situation that one side is safe but the other hits the anti-collision beam because the braking force is insufficient. The over wind side takes over more kinetic energy for system which is contrary to traditional experience. Then the relative installation positions of the overwinding and overwinding protection device should be settled down to improve the level of system security, the overwinding and overwinding protection devices are not in advance of each other, or a small amount of overwinding protection devices are in advance of the overwinding and overwinding protection devices. The conclusion above points out the blindness of the traditional design methods.

As the vertical hoisting system vary widely, a reasonable parameter matching and position matching should be done under a specific analysis and calculation.

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