Analysis of rope zone of multi-point multi-layer winding lifting system in ultra-deep mine

H L Wang¹,², X S Gong¹, Y Deng¹ and X R Cheng²

¹College of Mechanical Engineering, Chongqing University, Chongqing 400044, China
²College of Mechanical Engineering, Chongqing Technology and Business University, Chongqing 400067, China

E-mail: puma_hai@qq.com

Abstract. In the mining of ultra-deep resources, workers need to use ultra-deep mine lifting equipment to lift minerals, in order to ensure the synchronization between ropes during the lifting process. The article analyzes the change in the length difference between the steel ropes from the perspective of rope groove deformation. This work considers the influence of the weight of the vertical rope, analyzes the variation of surface load on the rope groove, establishes the expressions for deformation at the rope groove, and analyzes the influence of rope groove deformation on the difference in the length of the wire ropes. The results show that in the ultra-deep mine multi-layer winding lifting system, the rope groove load varies with the height of the rope. The rope groove deformation curve is similar to the quadratic function curve, and the maximum point is close to the middle position. Based on these results, the article studies the influence of the imbalance between the circles, the winding gap, and the rope-out method on the difference in the length of the wire ropes. It is found that, the extent of the lack of synchronization between the rings has a greater influence on the change in the length of the wire rope, and a wire rope wound under the reel is more conducive to ultra-deep mine lifting.

1. Introduction

Mineral resources have always been important as strategic national resources; demand for mineral resources tends to increase over time, and the mining industry in China continues to develop by mining to greater depths. At present, some countries have mines at depths varying from 2,500 to 4,000 m, and South Africa plans to conduct mining activities at a depth of 6,000 m [1]. However, the average mining depth in China is approximately 500 m. As shallow resources are consumed, the depth of mines in China will reach 2,000 m or more in the next 10 years. However, deep mining equipment has not yet met the basic requirements of payload, efficiency, and safety. For ultra-deep lifting, the design of new mine hoisting equipment is the bottleneck in deep resource mineral exploration [2-4].

In ultra-deep mine lifting, the single-rope-wound wire rope should have a large diameter, and it is difficult to manufacture. For the multi-rope friction type lifting system, the lifting capacity decreases as the lifting depth increases due to the influence of the stress amplitude. Therefore, it is necessary to use a multi-point multi-layer lifting system to analyze related problems, as shown in figure 1.

Due to high-speed and heavy-duty conditions, a variety of factors can cause the rope groove to deform, resulting in a difference in length between the ropes. Therefore, the aim of this study is to find a control method to reduce the deformation of the wire rope related with the roll rope groove structure.
In China and abroad, some researchers studied the deformation and stress on the reel. Gong [5] considered the support conditions by the analytical method and gave an accurate solution to the deformation and stress of the reel under uniform external pressure. Ge [6] established a static calculation model for the force of the reel, and analyzed the interaction between the rope loop and the reel. Gong [7] studied the force of the last wrapped wire rope on the reel as a concentrated force. Wang [8] analyzed the risk position of the reel and optimized it by applying a uniform load to the surface effect unit of the reel. Yang [9] proposed that for a single-layer wound spiral reel, due to the friction between the steel ropes, a gradual tightening force is exerted on a single rope groove, and the finite element analysis of the reel is carried out. Otto [10] studied the force of the wire rope on the reel and the end plate during the multi-layer winding process.

Although some researchers have studied the deformation of the reel, they simplify the load on the surface of the reel as a uniform load or a concentrated load, while others only study the single-ring rope groove. Ultra-deep mines have a lifting depth of more than 1500 m, and the diameter of the wire rope needs to be designed to ensure safe and stable operation of the lifting system under high-speed and heavy-load conditions. This makes the weight of the wire rope a factor that must be considered in the ultra-deep mine hoist system. Therefore, this study establishes the deformation formulas for a three-layer steel wire rope to reel rope groove. The influence of multi-layer winding of steel wire rope on the deformation of the winding rope in an ultra-deep mine hoisting system is then analyzed. Finally, by using the deformation formula, the influence of unbalance between the circles, winding gap, and rope-out method on the difference in the length of wire rope are analyzed.

2. Theoretical derivation

2.1. Mine hoisting system winding model

The ultra-deep mine makes it necessary to consider the weight of the wire rope during the lifting process. When the wire rope is wound onto the rope groove, its tension will cause the rope groove to be squeezed, thereby causing deformation of the rope groove. When the reel rotates, the wire rope is continuously wound on the rope groove; meanwhile, the weight of the wire rope in the mine will gradually decrease, which causes the tension in the wire rope on the rope groove to gradually decrease the load on the rope groove is a decreasing load. The side view of the ultra-deep mine hoisting system is shown in figure 2.
2.2. Winding zone stress model

As shown in Figure 3, the arc length of the rope groove in the circumferential direction is $Rd\phi$, and a unit positive pressure $dN$ acts on the reel. Since the angle $d\phi$ is small, it can be assumed that $\sin\left(\frac{d\phi}{2}\right) \approx \frac{d\phi}{2}$ [6].

Then, the positive pressure per unit area on the rope groove is $dN$, which can be obtained as:

$$dN = 2S \sin\frac{d\phi}{2} = Sd\phi$$

(1)

The radial unit pressure caused by the tension $S$ in the wire rope on the casing is:

$$q' = \frac{dN}{Rd\phi} = \frac{Sd\phi}{Rd\phi} = \frac{S}{R}$$

(2)

The pitch of the rope groove $t = d + \varepsilon$, where $d$ is the diameter of the wire rope and $\varepsilon$ is the gap between the rope rings in the rope groove. Set the $n$-turn wire rope within the unit distance:

$$t = \frac{1}{n}$$

(3)

The pressure on the unit area of the rope groove is:

$$q = q' \cdot n = \frac{S}{R} \cdot \frac{1}{t} = \frac{S}{R \cdot t}$$

(4)

It can be seen from the above formula that the radial pressure $q$ of the wire rope on the reel is related to the wire rope pulling force $S$, the drum radius $R$, and the rope groove pitch $t$. In other words, when the reel radius $R$ and the rope groove pitch $t$ are constant, the pressure $q$ on the rope groove is proportional to the wire rope pulling force $S$. Considering that the pressure on the reel is a uniform load, the pressure on the steel wire wrapped around the reel can be expressed as:

$$q = 2\pi R \cdot q' = 2\pi S$$

(5)

The absolute radial deformation caused by the shell under the tension of the steel wire rope loop of
$S$ is $y$, and the relative deformation of the shell in the circumferential direction is:

$$
\varepsilon_1 = \frac{2\pi(R - y) - 2\pi R}{2\pi R} = -\frac{y}{R}
$$

(6)

Then,

$$
Q = -\frac{E \cdot \delta}{R^2} \cdot y = -k \cdot y
$$

(7)

where $Q$ is the reaction force of the wire rope acting on the rope groove, $\delta$ is the thickness of the rope groove, $E$ is the elastic modulus of the rope groove, and $k$ is the basic coefficient of the radial elastic deformation of the rope groove, which can be obtained after simplification:

$$
k = \frac{E \cdot \delta}{R^2}
$$

(8)

It can be seen from equation (8) that the radial reaction force generated by the linear radial pressure of the rope groove is proportional to the radial deformation of the reel, which conforms to the deformation law of the elastic foundation beam, and the deformation of the reel can be simulated by the elastic foundation beam theory.

2.3. Winding curve deformation

2.3.1. Winding a first layer region of the rope deflection curve modification formula. Due to the weight of the vertical steel rope, the pressure on the rope groove decreases gradually. The force diagram is shown in figure 4, and the superscript ‘a’ indicates the first layer.

![Figure 4. Wire rope wrapped around the first section.](image)

From figure 4, the pressure of the first ring of the wire rope on the rope groove is $q_a$, and the pressure of the last ring of the wire rope on the rope groove is $q_n$. Since $\sum M_b=0$, we get:

$$
F_{RA}^a \cdot l_b = \frac{l_b^2 \cdot (2q_a + q_n)}{6}
$$

(9)

This formula can be reduced to:

$$
F_{RA}^a = \frac{l_b \cdot (2q_a + q_n)}{6}
$$

(10)

As can be seen from figure 4, the load set can be expressed as:
In summary, the bending moment equation of the rope groove under the gradual load is:

\[ M_{(x)}^a = \left( \frac{q_i^a - q_n^a}{6l_b} \cdot x + \frac{l_b(2q_n^a + q_i^a)}{2} \right) \cdot x \]  

(12)

Then, the curve of the rope groove can be expressed as:

\[ \omega = \int \int \left( \frac{M(x)}{EI} \right) dx \, dx + Cx + D \]  

(13)

This can be written as:

\[ \omega^a = \left( -\frac{(q_i^a - q_n^a)}{120l_b} \cdot x^2 - \frac{q_{13}^a}{24} \cdot x^4 + \frac{l_b(2q_n^a + q_i^a)}{36} \cdot x^3 \right) \cdot \frac{1}{EI^a} + C^a \cdot x + D^a \]  

(14)

From the boundary conditions: at \( x = 0 \), \( \omega_b = 0 \); at \( x = l_b \), \( \omega_b = 0 \); Thus: \( D^a = 0 \)

\[ C^a = -\left( \frac{7q_i^a + 8q_n^a}{360} \right) \cdot l_b^3 \cdot \frac{1}{EI^a} \]  

(15)

Finally, the curve of the rope groove under the gradient load is:

\[ \omega^a = \left[ \frac{-q_i^a - q_n^a}{120l_b} \cdot x^5 - \frac{q_{13}^a}{24} \cdot x^4 + \frac{l_b(2q_n^a + q_i^a)}{36} \cdot x^3 - \frac{(7q_i^a + 8q_n^a)}{360} \cdot l_b^3 \cdot x \right] \cdot \frac{1}{EI^a} \]  

(16)

2.3.2. Winding a second layer region of the rope deflection curve modification formula. When the wire rope is wound into the second layer, the winding direction is opposite to the winding direction of the first layer. In figure 5, the superscript ‘b’ indicates the second layer.

![Figure 5. Wire rope wrapped around the second section.](image)

From \( \sum M_A^b = 0 \), we get

\[ F_{RA}^b \cdot l_b = \frac{l_b^2 \cdot (q_i^b + 2q_n^b)}{6} \]  

(17)

Then:

\[ F_{RA}^b = \frac{l_b \cdot (q_i^b + 2q_n^b)}{6} \]  

(18)
The load set can be expressed as:

\[ q_{(s)}^b = \frac{q_n^b - q_i^b}{l_b} \cdot x + q_i^b \]  

(19)

In summary, the bending moment equation of the rope groove under the gradual load is:

\[ M_{(s)}^b = \frac{-(q_n^b - q_i^b)}{6l_b} \cdot x^5 - \frac{q_i^b}{2} \cdot x^3 + \frac{l_b(q_n^b + 2q_i^b)}{6} \cdot x \]  

(20)

Then, the equation of the curve can be written as:

\[ \omega^b = \left[ \frac{-(q_n^b - q_i^b)}{120 \cdot l_b} \cdot x^5 - \frac{q_i^b}{24} \cdot x^4 + \frac{l_b(q_n^b + 2q_i^b)}{36} \cdot x^3 - \frac{(7q_n^b + 8q_i^b) \cdot l_i^3}{360 \cdot l_b} \cdot x \right] \cdot \frac{1}{EI^b} \]  

(21)

2.3.3. Winding a third layer region of the rope deflection curve modification formula. Since the winding direction of the wire rope is the same as the winding direction in the first layer, the modeling process for the rope groove deformation is the same as that of the first layer. In contrast with the first layer, when the length of the wire rope in the mine is reduced and the rope layer grows on the rope groove, the tension in the wire rope gradually decreases and the moment of inertia of the rope groove gradually increases. Eventually, the rope groove is deformed when the third layer of the wire rope is wound on the reel. The force diagram is shown in figure 6, where the superscript ‘c’ indicates the third layer.

![Figure 6. Wire rope wrapped around the third section.](image)

The equation of the deflection curve is:

\[ \omega^c = \left[ \frac{-(q_i^c - q_i^c)}{120 \cdot l_b} \cdot x^5 - \frac{q_i^c}{24} \cdot x^4 + \frac{l_b(2q_i^c + q_i^c)}{36} \cdot x^3 - \frac{(7q_i^c + 8q_i^c) \cdot l_i^3}{360 \cdot l_b} \cdot x \right] \cdot \frac{1}{EI^c} \]  

(22)

In the above deformation formula, the moment of inertia I can be expressed as:

\[ I = \frac{\pi}{64} [(D_o + 2nd)^4 - D_i^4] \]  

(23)

where \( D_o \) represents the outer diameter of the reel, \( D_i \) represents the inner diameter of the reel, and \( n \) is the number of wire rope layers.

2.4. Load reduction factor
Changes in the tension cause deformation of adjacent loops, and the formula can be expressed as [7]:
\[
\Delta y' = \frac{\pi d^2 \phi F}{2k} e^{-\phi t} (\cos \phi t + \sin \phi t) \cdot \Delta y
\]

This can be reduced to:

\[
\Delta y' = \frac{\pi d}{8t} \Delta y
\]

(25)

To a certain extent, the tension is proportional to the deformation. So, the tension between adjacent wires can be expressed as:

\[
q_{n+1} = \frac{\pi d}{8t} \cdot q_n
\]

(26)

The rope ring load reduction factor of the adjacent ring wire rope can be expressed as:

\[
\gamma = \frac{\pi \cdot d}{8 \cdot (t + \delta)}
\]

(27)

where \( \delta \) indicates the offset gap between the ropes, so the load reduction factor of the end loop on the layer is:

\[
\gamma = (1-\varepsilon)^{n-1}
\]

(28)

Since the test string groove is wound \( n \) times per layer, the tension of the wire rope can be expressed as:

\[
q_n = q_1 \cdot \gamma
\]

(29)

where \( q_1 \) represents the load on the first rope groove, and \( q_n \) represents the load in the end rope groove.

3. Deformation of rope groove of prototype

In order to express the deformation state of the rope groove in the ultra-deep mine hoisting system more clearly, in this study, the parameters of the prototype model provided by the CITIC heavy industry are substituted into the theoretical formula for calculation. The prototype parameters are listed in Table 1.

| Physical quantity                                      | Numerical value               |
|--------------------------------------------------------|-------------------------------|
| Wire rope first layer initial ring load (q_{11})        | 9034659.2 (N)                 |
| Wire rope second layer initial ring load (q_{12})       | 8057906.685 (N)               |
| Wire rope third layer initial ring load (q_{13})        | 7117329.733 (N)               |
| Last loop load of each layer of wire rope (q_{n})       | \( \varepsilon \times q_1 \) (N) |
| Rope groove width (la)                                 | 2200 (mm)                     |
| Rope area width (lb)                                   | 2100 (mm)                     |
| Rope elastic modulus (E)                               | 2.0 \times 10^{11} (Pa)      |
| Rope groove outer diameter (Do)                         | 8000 (mm)                     |
| Rope groove inner diameter (Di)                         | 7600 (mm)                     |
| Wire rope diameter (d)                                  | 76 (mm)                       |
| Number of windings in the first layer                   | 27 (circle)                   |
| Number of windings in the second layer                  | 26 (circle)                   |
| Number of windings in the second layer                  | 27 (circle)                   |
Table 2. Prototype wrap rope area first layer load factor.

| Winding gap $\delta$(mm) | Loop load reduction factor ($\varepsilon$) | End loop load factor ($\gamma$) |
|--------------------------|------------------------------------------|-----------------------------|
|                          |                                           | level one | level two | level three |
| 0                        | 0.1917                                   | 0.00395   | 0.00489   | 0.00605     |
| 10                       | 0.1698                                   | 0.00792   | 0.00954   | 0.01149     |
| 20                       | 0.1525                                   | 0.01354   | 0.01598   | 0.01885     |
| 30                       | 0.1384                                   | 0.02079   | 0.02413   | 0.02801     |
| 40                       | 0.1266                                   | 0.02962   | 0.03391   | 0.03883     |

It is assumed that there are 0, 10, 20, 30, and 40 mm winding gaps (less than half-diameter of the wire rope) between the ropes during the winding process. According to equations (27) to (29), the calculation results of the load factor are summarized in table 2.

Subsequently, the parameters are substituted into equations (16), (21), and (22) for numerical simulation. Finally, the deformation results at the rope groove of the prototype under different winding gaps are obtained, as shown in figure 7.

Figure 7. Prototype machine twisted area triple deflection curve deformation.

As can be seen in figure 7, with an increase in the number of winding layers, the influence of the wire rope on the deformation of the rope groove is gradually reduced. As the reel runs, the wire rope is wound around the reel and the surface of the rope groove is affected by the gradient load, the maximum deformation of the rope groove is basically in the middle position, and the deformation curve is in the form of a quadratic function. The deformation of the rope groove increases as the winding gap increases, but it can be seen from the calculation results in the figure that the winding gap between the ropes has little effect on the deformation of the rope groove.

4. Variation of wire rope length difference between two rope grooves

Due to the deformation of the rope groove, the length of the wire rope at the two rope grooves on the reel changes. This section studies the variation of wire rope length difference when there are winding gaps under different rope-feeding modes and wire rope winding is not synchronized between two rope grooves.

4.1. Analysis of length difference of wire rope under winding gap condition

During winding, the difference in the angle of the rope will cause the length of the rope to change when the wire rope is wound under the reel.
As shown in figure 8, the deformation of the rope groove during winding of the wire rope is recorded as $\delta_R$, then the deformation of the wire rope is:

$$\delta_w = \delta_R \times \cot \alpha$$  \hspace{1cm} (30)

For the case where the wire rope is wound on the reel, the winding mode is shown in figure 9. As shown in figure 9, the deformation of the rope groove during winding of the wire rope is recorded as $\omega$, and the deformation of the wire rope is:

$$\delta_w = \omega \times \tan \alpha$$  \hspace{1cm} (31)

For the case where the wire rope is wound under the reel and the winding gaps are set to 10, 20, 30 and 40 mm, the length difference of the wire rope is shown in figure 10.

In the same way, when the wire rope is wound upon the reel, the difference in length of the wire rope is shown in figure 11. It can be seen from figures 10 and 11 that the difference in length of the wire rope varies in a parabolic manner. When the wire rope is wound into the middle of the rope groove, the difference in the length of the wire rope is maximized. It can be seen from the figure that the change in the length difference of the wire rope is most obvious when the wire rope is wound on the first layer. When the winding gap of the wire rope is continuously increased, the difference in length also increases continuously. The difference in the length of the wire rope upon the reel is greater than which under the reel, and the difference in the length of the wire rope upon the reel is about twice of that under the reel.
4.2. Analysis of wire rope length difference under the unsynchronized winding of the ropes

When the wire ropes in the rope grooves on both sides have an inter-circle displacement during the winding process, the rope ring load reduction coefficient changes, which leads to a length difference between the wire ropes.

This section studies the influence of the unsynchronized winding of the ropes in the left and right ropes on the length difference of the ropes, when the wire rope is wound under the reel, and does not consider the winding gap. As there are one to two turns out of sync, the difference in wire rope length is shown in figure 12.

![Figure 12. Difference in length of the wire rope when the rope is under the reel.](image1)

![Figure 13. Difference in length of the wire rope when the rope is upon the reel.](image2)

When the wire rope is wound upon the reel, the length difference of the wire rope is shown in figure 13, as there are one to two turns out of sync.

It can be seen in figures 12 and 13 that, when wire ropes in the two rope-wrapping areas are not synchronized with each other, the length difference variation of the wire ropes can be described by a trigonometric function. As can be seen from the figure, the difference in length of the wire rope is greatest at the beginning and end of the rope groove, and smallest at the middle of the rope groove. As the lack of synchronization in the wire rope increases, the difference in wire rope length gradually increases. As can be seen from the figure, the difference in the length of the wire rope upon the reel is greater than that under the reel, and the difference in the length of the wire rope upon the reel is about twice of that under the reel. Comparing the results in Section 4.1, the lack of synchronization between the wire rope rings has a greater influence on the change in the wire rope length difference.

5. Conclusions

- This paper establishes a deformation formula for the rope groove under a load gradient, and extends this model to the ultra-deep mine hoisting system.
- The rope groove is under a gradient load, and the position of maximum deformation is in the middle. In order to reduce the deformation of the rope groove, designers need to strengthen the structure of the middle part of the rope groove.
- The extent of asynchronization between the rings has a greater influence on the change in the length of the wire rope. Therefore, in the process of ultra-deep well lifting, it is necessary to ensure that the wire rope synchronization is within one revolution.
- When the wire rope is wound under the reel, the difference in length of the wire rope will be smaller, which is more conducive to ultra-deep mine lifting.

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