Research on Fiber Tension Control based on Fiber Winding Equipment

Abstract: With the continuous improvement of the sensing accuracy of optical fiber sensing products, the continuous increase of optical fiber length, and the continuous miniaturization of fiber coil volume, the difficulty of producing fiber coils is also increasing. At present, the common method for the production of fiber coils in China is to use semi-automatic production equipment, each piece of equipment is equipped with one to two operators, and the whole process is semi-manual production. The production of each fiber coil takes several hours to tens of hours. In this process, fiber tension is an important technical index to determine the performance and quality of the fiber coil. This paper studies the tension control method and the principle of the existing fiber winding equipment, and puts forward its shortcomings and improvement schemes, which is conducive to further improving the fiber tension control accuracy of the fiber winding equipment, and provides a technical reference for the automatic winding equipment, which meets the development needs of the continuous improvement of the performance of the fiber coil and the continuous increase in output.

Keywords: Fiber winding; optical fiber; tension; fiber coil; automation;

The core sensing element of optical fiber sensing products in many fields, such as fiber optic gyroscopes, fiber optic hydrophones, and fiber optic delay coils, is the fiber coil. The fiber coils of different optical fiber sensing products have great differences in size specifications and process requirements, but their performance and production process have an important technical index - fiber tension. Fiber tension has a great impact on the performance of the fiber itself and its products. Therefore, how to accurately control the fiber tension has become an important issue for the fiber winding equipment.

The optical fiber processing flow of different optical fiber sensing products is similar. Taking the fiber optic gyroscope coil as an example, the optical fiber processing flow is shown in Figure 1:

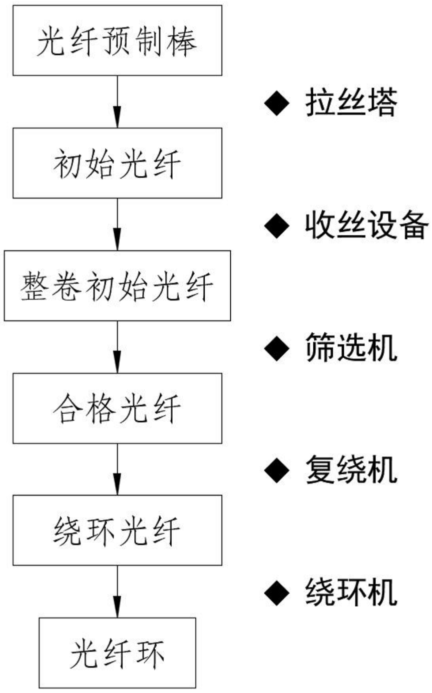

Figure 1. Optical fiber processing flow

First, the optical fiber preform rod is drawn on the drawing tower to form the initial optical fiber of the specified specification, and then it is wound into a whole roll of initial optical fiber through the take-up equipment in turn. The qualified optical fiber is screened by the screening machine, and the large-scale qualified optical fiber is divided into several by the rewinding machine. The small-coiled optical fiber is finally installed on the coil winding machine to form the fiber optic gyroscope coil. Among them, precise tension control is required for the take-up equipment, the screening machine, the rewinding machine and the coil winding machine. Otherwise, due to unstable tension and excessive fluctuations, the optical fiber products processed by the equipment are easily damaged or even scrapped.

1. Detection method for fiber tension

At present, there are three common schemes for fiber tension control in China:

(1) Swing rod + angle sensor

Figure 2 is a schematic diagram of a tension swing rod of a single fiber guide wheel structure. One end of the swing rod is provided with a fiber guide wheel, and the other end is provided with a counterweight. The fiber guide wheel and the counterweight can swing along the rotation axis on the swing rod within a certain angle. When the swing rod is in the horizontal position, the fiber guide wheel and the fixed wheel can be vertically tangent through an optical fiber (for intuitive understanding, the guide wheel does not show the V-shaped groove in the figure). According to different requirements of fiber rewinding speed, the combination of the fiber guide wheel and the fixed wheel can be a single wheel or a multi-wheel combination, and the corresponding guide wheel layout positions are also different, but the principle of fiber tension detection is the same.

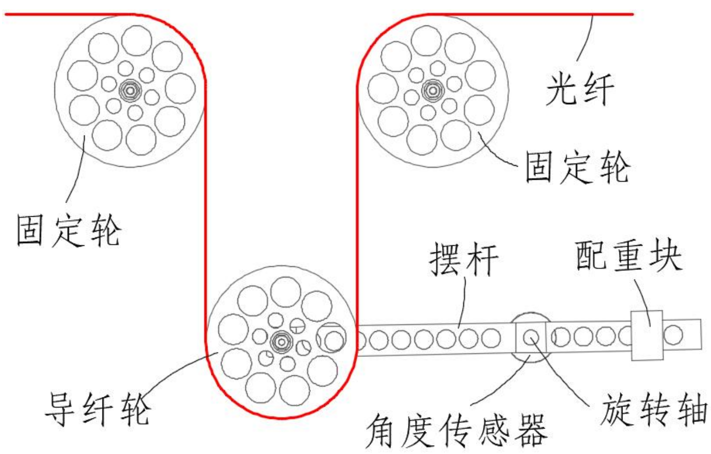

Figure 2. Schematic diagram of tension swing rod

The angle sensor can be an angle measuring device, a potentiometer, an encoder, an analog proximity switch, or even multiple switch proximity switches distributed uniformly in an arc shape. With a specially designed mechanical structure, the current swing angle of the swing rod can be measured directly or indirectly. The detection accuracy of different angle sensors varies greatly. The resolution of the sensor with poor accuracy is only a few degrees, and the resolution of the sensor with good accuracy can be up to one-thousandth of a degree.

When the optical fiber passes through the fiber guide wheel, due to the special guide wheel structure arrangement on the equipment, assuming that the swing rod is in a horizontal position and the self-weight of the left and right arms of the swing rod are equal, and the friction force of the guide wheel bearing is 0, combined with the principle of leverage, the formula can be obtained:

$$\left(F_{导轮重力} - F_{光纤张力} \times N_{光纤段数}\right) \times L_{导轮力臂} = F_{砝码重力} \times L_{砝码力臂}$$

$$F_{光纤张力} = \left(F_{导轮重力} - F_{砝码重力} \times L_{砝码力臂} / L_{导轮力臂}\right) / N_{光纤段数}$$

Since the other parameters except for the fiber tension in the formula are known constants or can be specifically measured, the fiber tension when the swing rod is balanced can be calculated. In practical applications, the tension fluctuation detection accuracy of this scheme can reach 0.1g.

(2) Swing rod + cylinder + angle sensor

The structure of this scheme is similar to scheme 1, and the main difference is that the counterweight is replaced with a precision cylinder assembly. The cylinder is connected with compressed air, and the pressure of the cylinder can be adjusted through the pressure regulating valve to adjust the force acting on the counterweight side of the swing rod, thereby indirectly adjusting the given fiber tension. When the swing rod is horizontal, the formula is as follows:

$$F_{光纤张力} = \left(F_{导轮重力} - F_{气缸压力} \times L_{气缸力臂} / L_{导轮力臂}\right) / N_{光纤段数}$$

Similarly, the other parameters except for the fiber tension in the formula are known constants or can be specifically measured, so the fiber tension when the swing rod is balanced can be calculated. In practical applications, the tension fluctuation detection accuracy of this scheme can reach 0.5g.

The main difference between scheme 2 and scheme 1 is that the lever counterweight value of scheme 1 can only be roughly adjusted when the equipment is shut down, and the position of the counterweight needs to be moved manually, which is troublesome and difficult to adjust to the accurate target tension value; and the lever counterweight value of scheme 2 can be accurately adjusted online and in real-time, and can be adjusted through the touch screen or the pressure regulating valve, and even the target given tension can be automatically adjusted through the program setting, which is convenient and quick to operate.

(3) Spring + tension sensor

By introducing the special tension sensor module into the optical fiber travel path and cooperating with the relevant mechanical structure and software algorithm, the real-time detection and given optical fiber tension can be realized. Figure 3 and Figure 4 are schematic diagrams of the layout of the tension sensor of the quadrupole coil winding machine. Among the several guide wheels through which the optical fiber passes, there is a tension wheel, which is connected to a tension sensor to collect the fiber tension passing through the guide wheel; there is a balance wheel downstream of the tension wheel, which is connected with the swing rod, the rotating shaft, and the spring to provide the fiber tension and the buffer stroke required in case of tension fluctuation.

According to Hooke’s law, within the elastic limit, the elastic force F of the spring is proportional to the elongation change x of the spring, that is, $F=kx$, where k is the elastic coefficient of the spring. Therefore, selecting the appropriate spring determines the swing angle of the swing rod and the range of tension value provided by the spring to the optical fiber.

Using this tension control scheme in practical application, the fiber tension can be accurately obtained by suspending standard weights and data calibration, and the tension detection accuracy can reach 0.2g.

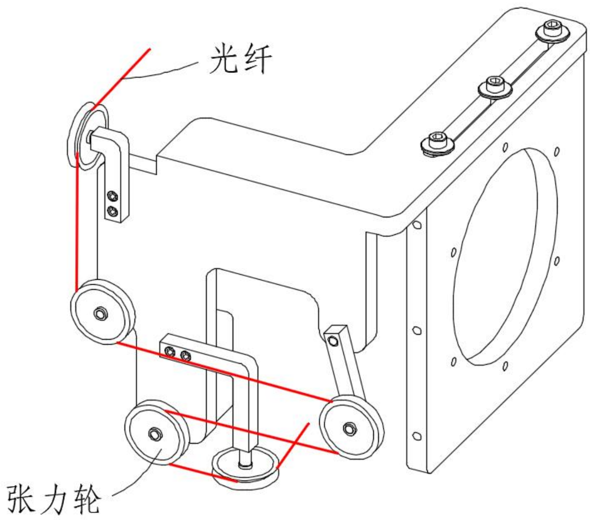

Figure 3. Schematic diagram of the layout of the tension sensor (front)

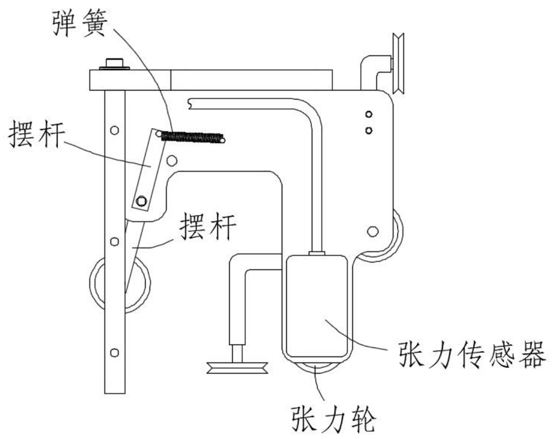

Figure 4. Schematic diagram of the layout of the tension sensor (back)

The difference between scheme 3 and scheme 1 and 2 is that in scheme 1 and scheme 2, fiber tension is provided by gravity, and the angle of the swing rod is detected by the angle sensor to sense the amplitude when the tension deviates from the balance position of the swing rod; in scheme 3, fiber tension is provided by spring force, and the fiber tension is directly detected by the tension sensor.

2. Fiber tension control algorithm

Fiber tension detection is only the first step of fiber tension control. The next step is to analyze and process the collected data through the electrical control system, and deliver the processing results to the execution components of the equipment for execution, such as the speed-regulating rotation of the fiber rewinding/unwinding motor and the adjustment of the displacement rate of the fiber discharging machine, etc., finally realize the specified fiber winding action under the condition of precise control of the take-up tension.

For the above three fiber tension control schemes, the program control algorithms used are almost the same. Take scheme 1 as an example for analysis. Firstly, according to the motion trajectory of the swing rod, the reasonable upper and lower limit positions and balance positions are selected, and the angle sensor data are collected respectively. The balance position generally selects the horizontal position, and the upper and lower limit positions are set symmetrically relative to the balance position, as shown in Figure 5. For a well-adjusted device, the angle sensor data between the upper and lower limit positions are linearly distributed, and the data can be processed into the data between 0%~100% corresponding to the lower limit and upper limit of the swing rod as shown in Figure 5, and the balance position is exactly 50%.

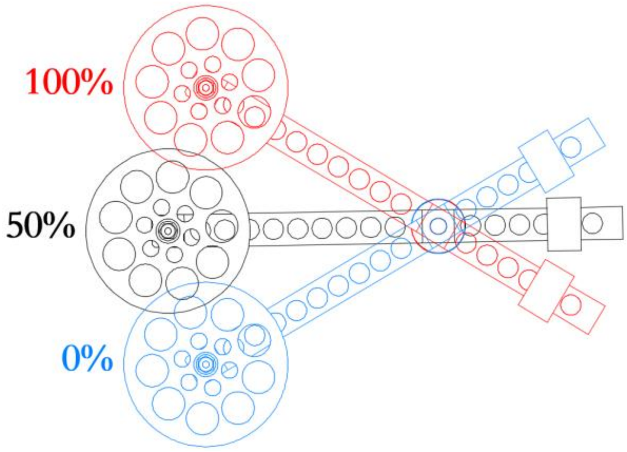

Figure 5. Schematic diagram of the swing range of the swing rod

Then, PID calculation is configured in the control program. PID calculation is a control algorithm that operates according to the functional relationship of the deviation proportion (P), integral (I) and differential (D), with mature technology and wide application. The calculation formula is as follows:

$$u(t) = K_p \left(e(t) + \frac{1}{T_t} \int_0^t e(t)dt + T_D \frac{de(t)}{dt} \right)$$

Where: K_p - Proportional gain; T_t - Integral time constant; T_D - Differential time constant; $u(t)$ - PID controller output signal; $e(t)$ - The difference between the given value and the measured value.

In actual industrial applications, the calculation formulas are integrated by the corresponding standard program blocks, and the technicians only need to configure the corresponding parameters and control programs. Figure 6 shows the PID parameter configuration of Siemens 1215PLC on a certain fiber winding equipment, and Figure 7 shows the corresponding PID control program block.

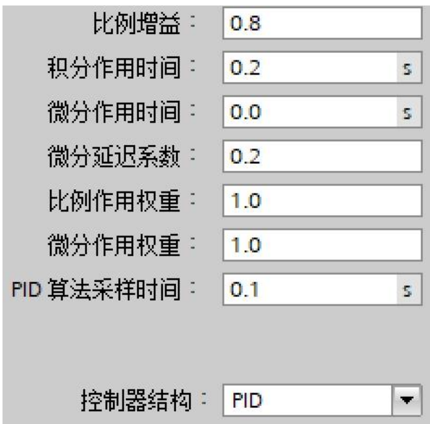

Figure 6. PID parameter configuration

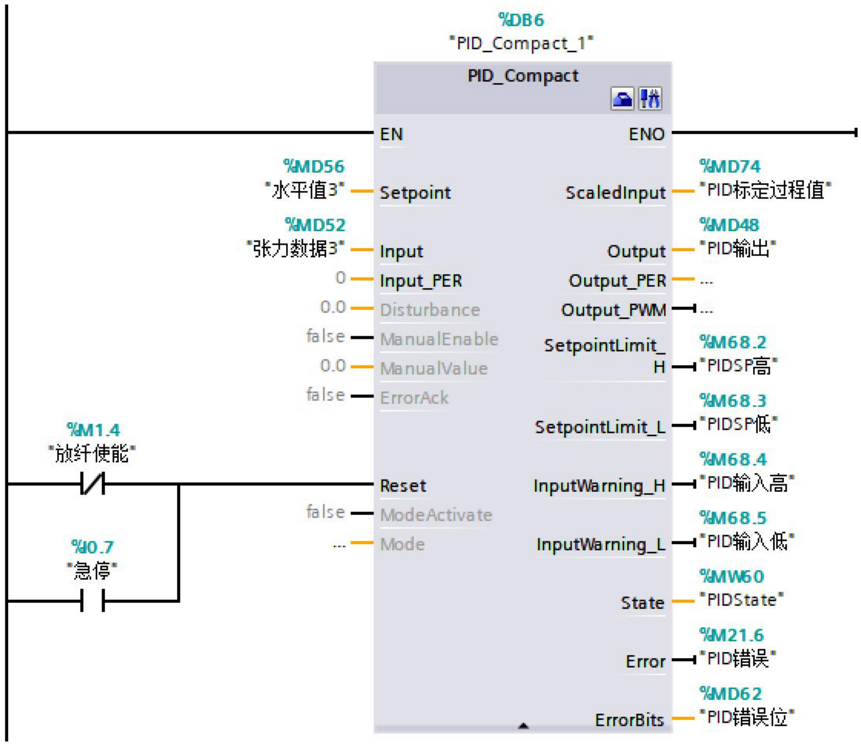

Figure 7. PID program block

After configuring the PID parameters, it is also necessary to design a complete control program and carry out a series of system configurations to finally drive the equipment to operate normally. Figure 8 shows the swing amplitude curve of the swing rod processed by the PID controller, and the control objective is to make the swing rod in a horizontal position, that is, 50% amplitude. If the PID parameters are not configured properly, it will lead to excessive control or weak control. Excessive control will cause frequent oscillations of the swing rod, causing large fluctuations of the fiber tension, and in severe cases, the motor will stall and break the fiber; weak control will slow the system response, making the equipment rewinding and unwinding of the fiber process sluggish, and it is easy to trigger the upper and lower limit alarms of the swing rod and cause shutdown. With appropriate PID parameter configuration, the PID control curve will be the same as the green curve in Figure 8, reaching the control target position quickly and steadily, and the corresponding equipment's process of rewinding and unwinding the fiber will also be smooth in speed and be stable in tension.

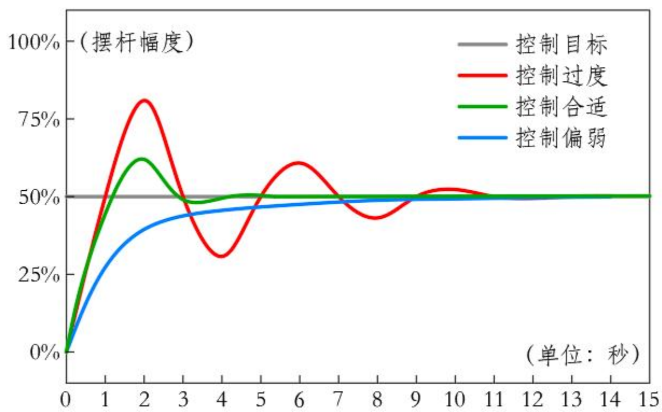

Figure 8. PID control curve

PID control algorithm is a relatively simple and effective feedback control algorithm in the field of automatic control at present. In addition to the PID control algorithm, there are many other control algorithms with the same purpose, which is to control the target object within a given range quickly and steadily.

The fiber tension control algorithm in scheme 3 is similar to the above method. Firstly, the tension lower limit, target tension, and upper tension limit of the tension wheel are calibrated, and then PID configuration, system configuration, control program design are carried out, and finally, the tension in the winding process is stabilized by balancing the data relationship between the motors, sensors and other components.

3. Further analysis and improvement

In the aforementioned fiber tension control schemes, in schemes 1 and 2, the fiber tension is provided by gravity, and the angle of the swing rod is detected by the angle sensor to sense the amplitude of the tension deviating from the balance position of the swing rod. Scheme 2 has improved the counterweight method of scheme 1 so that the lever counterweight value can be accurately adjusted online and in real-time. However, in practical application, scheme 2 compared to scheme 1 introduces another defect, that is, the cylinder pressure in scheme 2 is difficult to achieve absolute stability in practical application. There will be slight fluctuations affected by temperature, air pressure, vibration, etc., which is equivalent to the $F_{\text{cylinder pressure}}$ in the aforementioned fiber tension calculation formula, which is a parameter with small random errors. Whether the swing rod is swinging or in a static state, the error persists, resulting in a decrease in the accuracy of tension detection. Therefore, the tension fluctuation detection accuracy of scheme 1 can reach 0.1g, while that of scheme 2 can only reach 0.5g.

On the other hand, due to the characteristics of the swing rod rotating around the axis, the gravity decomposition will be caused when the swing rod is in a non-horizontal state. As shown in Figure 9, ignoring the bearing friction, when the swing rod is in the horizontal position, the force F1 on the optical fiber is equal to the gravity G of the swing rod at the guide wheel; when the swing rod is in the non-horizontal position, it can be seen from the force decomposition (parallelogram rule of force) that the force F1 on the optical fiber is only a component of gravity G, and there is another component F2 acting on the swing rod. The greater the angle of the swing rod deviates from the horizontal position, the greater the F2. The size and direction of G are constant, while that of F1 and F2 change with the angle of the pendulum. Moreover, due to the change of the angle between the fixed wheel and the balance wheel, the actual axial tension on the optical fiber requires a new round of force decomposition of F1, which leads to too many variables and is too complicated for the fiber tension control model, which is not conducive to precise control of fiber tension. This is also the reason why the precondition that the swing rod is in a horizontal position is emphasized in the aforementioned fiber tension calculation formula.

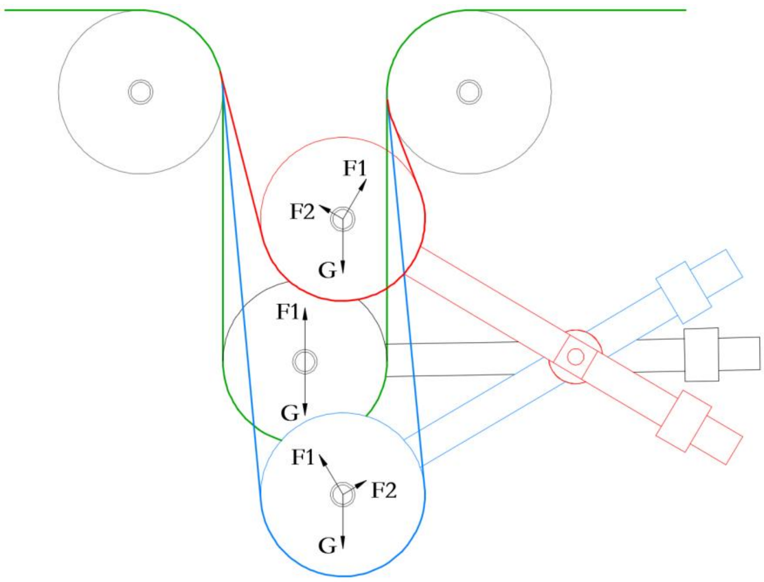

Figure 9. Schematic diagram of swing rod position and force analysis

Schemes 1 and 2 can only give the fiber tension, and judge whether the changing trend of the current tension is greater than or less than the given tension at the balance position under dynamic conditions, so real-time tension cannot be truly detected. The direct control object of the aforementioned fiber tension control algorithm is the swing rod angle data, and the fiber tension is only an indirect control object. And if the stability of the swing rod of the equipment is not well controlled, the angle of the swing rod deviating from the balance position will be too large or swing frequently. According to the aforementioned analysis, the tension on the fiber will fluctuate significantly, which is equivalent to continuously applying varying tension to the optical fiber. For winding operation, if this changing tension is continuously applied to the fiber coil and packaged and solidified into the fiber coil under the surface tension of the adhesive during the synchronous gluing process, it will inevitably lead to uneven tension distribution on the fiber coil. Especially in the process of starting and stopping, acceleration and deceleration of winding coils, due to the excessive and rapid changes in the angle of the swing rod and the excessively high swing frequency of the swing rod, this tension change becomes more severe. This is also the fundamental cause of the problems in equipment such as the inconsistent quality of the fiber coil products and the difficulty in precise control of performance.

To minimize the change of fiber tension, the measures that can be taken are to increase the length of the side swing rod of the balance wheel, increase the number of fixed wheels and balance wheels (increase the number of fiber sections to reduce the fluctuation angle of the swing rod under the same fiber displacement condition), reduce the angle and frequency of the swing rod deviating from the horizontal position during the operation of the device through high-precision mechanical assembly and electrical control. The improved scheme 1 is suitable for winding high-precision fiber coil products on semi-automatic machines and other winding devices such as fiber separators. Scheme 2 is suitable for winding machines, screening machines, etc., which often adjust fiber tension according to different types of optical fibers and require relatively low tension control precision.

Compared with schemes 1 and 2, in scheme 3, the fiber tension is provided by the spring force, and the fiber tension is detected directly by the tension sensor. Therefore, scheme 3 can not only give fiber tension online at any time but also detect the real-time tension of the balance wheel at any position. The direct control object of its fiber tension control algorithm is fiber tension. In terms of working principles, it has improved a lot compared with schemes 1 and 2. However, scheme 3 also has some shortcomings.

The tension sensor in scheme 3 generally has a force angle requirement and only detects the force applied to the force point in the positive direction. Therefore, the arrangement of the guide wheel is very important to ensure that the fiber tension direction always coincides with the force detection direction of the sensor. The arrangement of the guide wheel shown in Figures 3 and 4 will lead to a significant change in the optical fiber angle between the balance wheel and the tension wheel due to the swing of the swing rod. As shown in Figure 10, the tension value detected by the sensor is inevitably only a component of fiber tension on the direction of force applied to the sensor, rather than the actual tension value on the optical fiber. The error increases as the angle of the swing rod deviates from the vertical position increases.

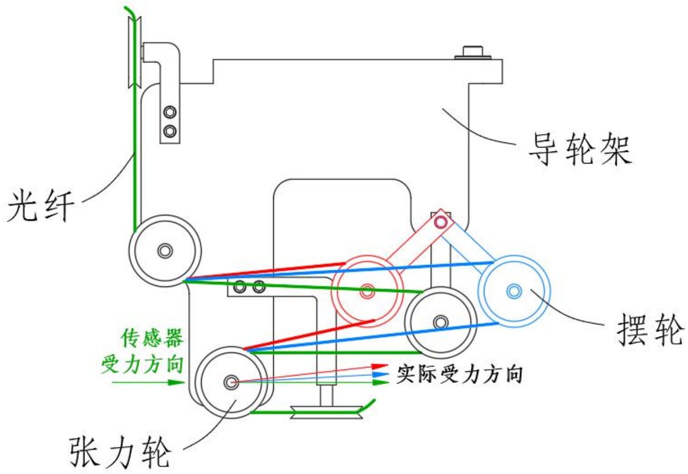

Figure 10. Schematic diagram of balance wheel position and fiber angle

On the other hand, although in scheme 3, the fiber tension is provided by spring force, in the process of practical application, because the whole guide wheel frame rotates around the principal axis, the fiber tension is provided by the gravity of spring and balance wheel mechanism. Moreover, the force transmitted by the gravity of the balance wheel mechanism to the optical fiber will continue changing with different swing rod angles and different positions of the guide wheel frame around the principal axis, and the change is aggravated as the speed of the guide wheel frame around the main shaft increases.

The fiber tension detection error introduced by the aforementioned swing rod angle deviation and the changing fiber tension introduced by the gravity of the balance wheel mechanism lead to the data detected by the tension sensor not matching the actual fiber tension value completely, which makes it difficult to make sure the actual fiber tension value stable, even under the high-precision mechanical adjustment and electrical control algorithm. At present, the stable tension curve on the quadrupole winding equipment designed according to scheme 3 can only be regarded as the data detected by the tension sensor to achieve a smooth effect, and it does not mean that the actual fiber tension is also stable. This is the fundamental reason why the quadrupole winding equipment designed according to scheme 3 can only achieve medium and low precision winding and it is difficult to improve the winding speed.

To give full play to the advantages of the tension sensor and avoid the interference caused by the swing of the swing rod, the improvement idea of scheme 3 is to replace the swing wheel mechanism with another guide wheel moving mechanism. The mechanism will not cause deviation between the tension direction of the optical fiber and the force direction of the sensor, and the changing gravity will not be introduced into the fiber tension due to the rotation of the guide wheel frame or the movement of the guide wheel.

Figure 11 is a schematic diagram of a structural improvement for Scheme 3. The original balance wheel structure is replaced by spring (compression spring), groove, slider and guide rod. With the fiber tension, the pulley can achieve a balanced state through the guide rod and the slider compression spring along the groove parallel to the direction of the sensor, to stabilize the given fiber tension. The force direction of the given fiber tension of this structure is always consistent with the force direction of the tension sensor, and gravity will not be introduced into the fiber tension due to the rotation of the guide wheel frame or the movement of the pulley, which conforms to the aforementioned improvement idea. The improved scheme can not only be modified and upgraded on existing equipment to realize the winding of medium and high-precision fiber coils and increase the winding speed but also can be applied to fully automatic coil winding equipment. The only problem to be solved in practical application is how to select the appropriate parts and design the corresponding structure so that the resistance of slider movement can be ignored.

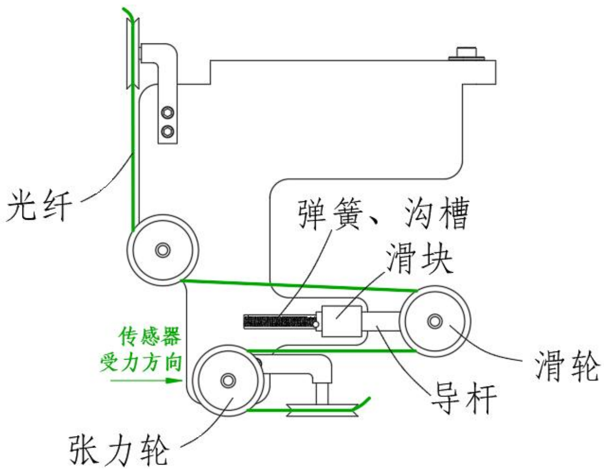

Figure 11. Schematic diagram of structural improvement of scheme 3

4. Conclusion

If the fiber optic gyroscope is a treasure among fiber sensors [1], then the fiber coil is the most shining pearl on this treasure. Whenever I think that I have also participated in the construction of this high-tech and national defense cause, I am proud of myself and feel excited. However, due to the late start and little experience of the domestic optical fiber sensing industry, there is still a big gap with western scientific and technological powers in the accuracy and automation of winding equipment. At present, there are also some researches on winding equipment and its tension control in China, such as using piezoelectric ceramic micro motion platform to control fiber tension [2], using the principle of electromagnetic induction between the magnet and energized coil and the fiber tension adjusting device of ranging grating ruler [3]. However, it is not easy for these technologies to be stably and effectively applied to the actual production process. The road ahead will be long, our climb will be steep. As a technician, we must cherish time, grasp research opportunities, devote ourselves to research, study rigorously, forge ahead bravely and catch up, to contribute to the development of national optical fiber sensing technology.

References:

[1] Zhang Guicai. The principles and technologies of fiber-optic gyroscope[M]. Beijing: National Defense Industry Press, 2010

[2] Liu Liangjian. Research on high precision tension control in the process of optical fiber winding[D]. Harbin Institute of Technology, 2015

[3] Guo Weihua, Yin Li, etc. Optical fiber tension regulating device [P]. Chinese Patent: ZL201810062060. 4, 2018