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Design Of the Tension Mechanism Of a Knotter And Optimization Of the Motion Parameters

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Abstract
Currently, the knotting of chemical fiber filament packages in factories primarily comprises manual operations. It also has a high labor intensity and is subject to artificial subjective factors, due to which it is difficult to guarantee the quality of the finished fiber products. Furthermore, it also significantly restricts the intelligent construction of chemical fiber production. This work employs partially oriented yarn (POY) and full draw yarn (FDY) to develop an automatic knotting device. The catenary theory was used to confirm the state of the yarn and to determine the relevant parameters of the tension mechanism. The results showed that the developed automatic knotting device satisfactorily meets the conditions required for manual knotting. The curve equation that was calculated using the catenary conformations of the yarn state verified that the actual yarn state was consistent with the theory. Moreover, the work provides a theoretical foundation for subsequent mechanism optimizations.

Keywords
chemical fiber filament, knotter, catenary, knotting rate.

1. Introduction

During the “13th Five-Year Plan” period, several iterations of automated equipment such as the intelligent drop-off system, intelligent shovel board system, intelligent spray plate detection, and assembly component system, online quality inspection and management system, intelligent packaging system, the intelligent automated warehouse and the transportation system have been widely utilized by chemical fiber enterprises in China. However, there are also types of automation that the intelligent knotting system has not realized as yet. The term ‘knotting’ could refer to the knotting of one linear fabric or the knotting and connection of two linear fabrics. Relying on workers for knotting is not only expensive, but the quality of the knots is also low. It is therefore necessary to develop a fully automatic silk knotting device. Knotters have been widely studied and applied in many industries, for instance, forage binding in agriculture and animal husbandry [1-7]. The knotters used in forage binding in agriculture and animal husbandry are generally D-type knotters. Many researchers have worked on D-type knotters and a series of studies were carried out on the principle of bonding, gear-disc performance, mechanism motion characteristics, and spatial parameters, and several important research results were obtained. They are also used in surgical stitching and ligation in the medical and health industry [8]. Wang et al [9] studied knotting behaviour in supporting the larynx in a minimally invasive throat surgery to carry out robot-assisted stitching. Chen et al [10] studied the mechanics of kelp and the design of the knotting mechanism. Wang et al [11] used the spiral claw method to knot the kelp. Chen et al [12] studied the knot-forming mechanism and developed a new knotter. The research on the knot-forming mechanism is mainly divided into two types: research on the topological representation of the knot and research on rope support, both of which complement each other [13-15]. Many researchers have carried out extensive research on knotting [16-19]. Luo et al [20] analyzed the performances of knotting devices in various fields and carried out extensive investigations of the knotting object used by automatic roving knotting devices. Based on their analysis, they designed a liquid glue adhesive knotter mechanism. Knotting is classified into four main types. Namely, traditional mechanical knotting, adhesive bonding, hot melt connection, and air bonding. With different knotting mechanisms, the principle of working with each type is different. In the case of glue bonding, hot melt connection, and air bonding, the knotting is carried out at the ends so that it is not easily removable. Package knots take ease of use into account and certain requirements were demanded so that it could be tied into a live knot, which implies that pulling the formation of the knots along the line head could remove the knot and return to its original state. However, the live knot could result in knots becoming loose due to being handled by workers or transportation vibration. This could have a significant impact on subsequent wire detection and transportation. Based on the three-dimensional model of the knotting mechanism, the relevant parameters of the wire tension mechanism were determined using the catenary equation to verify that the designed tension mechanism could complete the tightening action. Further, for the follow-up, institutional optimization would provide a good foundation, to achieve full automation of the chemical fiber industries. In addition, as a follow-up, optimization carried out within individual institutions would provide a good foundation for achieving the full automation of chemical fiber industries.

2. Methods

The current use of the silk fixation method in these enterprises is much more complex, however, the silk fixed knots are reliable and not loose. Further, the operator of the next procedural step could quickly find the fixed position of the silk head and quickly restore the silk head shedding state, thus the silk could be resumed back to normal. The package fixing device automatically completes the silk head fixation, and its silk head fixing state is expected to be reliable and not damaged by unforeseen factors, so it enables the personnel involved in the next step of the procedure to easily return the silk cake to a normal de-winding state. Further, as the package is distributed side by side on the silk car, the space between the adjacent packages is small. Therefore, the design of the silk-fixing device should meet the dynamics required for normal operation without touching the surfaces of the packages.

2.1. The chemical fiber filament knotting process

To make the design of the knotting procedure more practical, in each chemical fiber factory, artificial knotting is monitored to ensure that their peeling and silk fixing processes are similar. Initially, the package is picked up using a manipulator and placed into a silk car. The silk car comprises two sides: A and B, each of which has two sides. Each side has a total of three layers, however, the number of layers is not fixed. Each layer is designed according to the manufacturer's requirements, wherein some of the layers store four packages, while the others store five. Based on the variety of packages, the distance between them varies. In addition, workers initially arrange all the package silk heads on one side of the silk car and then complete the silk-stripping action of the package around the surface by sucking the fixed silk through the suction gun. Finally, workers knot each package. The entire package knotting time takes about 2 seconds. As manual knotting requires workers to constantly squat down and stand up, it is inevitable that the efficiency of workers will decrease over time. Therefore, the development of an automated knotting device to replace the labour force would promote the intelligent development of the chemical fiber production process.

To distinguish the direction, the package space diagram is shown in Figure 1. In Figure 1, the YOZ face is considered to be the front plane.

The machine knotting process is shown in Figure 2. The entire manual knotting process is divided into eight steps as follows: Initially, the left hand of the mechanism picks the package silk head, and the right hand rotates counterclockwise around the YOZ surface to complete the picking line. Then, the right hand wraps around the XOY face that rotates clockwise 270° to form a node coil. In addition, the right hand passes through the node coil and hooks the left-hand silk, while the left-hand silk passes through the node coil to form a transition coil, and the right hand passes through the transition coil and hooks the left-hand silk. Finally, the left-hand silk forms a tension coil through the transition coil, and the tension coil tightens into a knot to complete the break.

The difference between a knot made manually and by a machine is shown in Figure 3. From the figure, it is observed that the artificially formed knot is not different from the machine-formed knot, however, the machine-formed knot is more stable. The artificially formed knot could sometimes be either tight or loose.

The knotting device is divided into two parts: the knotting mechanism part and the control system. The knotting mechanism is composed of four sub-bodies including the silk breaker responsible for cutting the silk that forms the knot, the ringing mechanism responsible for the formation of the coil, the tensioning mechanism responsible for tightening the formed coil into knots, and the picking mechanism responsible for provoking the coil and becoming a part of the tension mechanism. The schematic diagram of the entire knotting mechanism control is shown in Figure 4. The entire knotting mechanism is controlled by cylinders and servo motors and combined with the nozzle, which completes the knotting action.

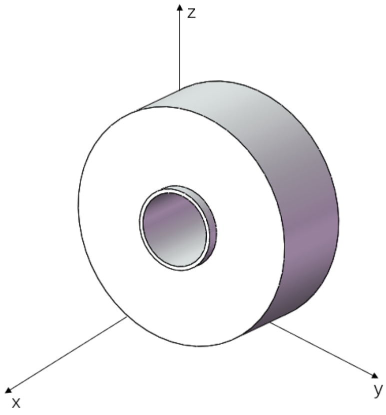
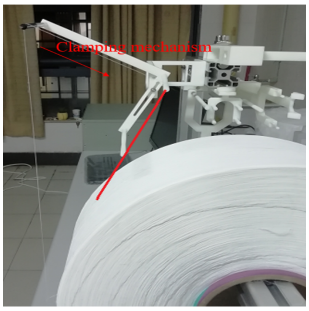


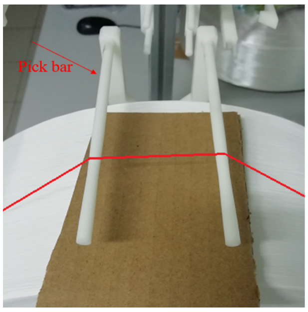
Fig. 1. Schematic representation of the package space

2.2. Design of the Chemical fiber filament tension mechanism

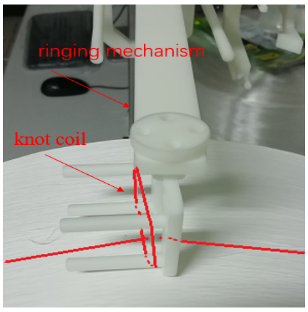
When the knotting device was being designed, the length of the cylinder was fixed during the tightening process. After the formation of a tension coil clamping, a transition coil cylinder was considered to provide the silk. Until the completion of this process, the tension coil was not provided with tension at the initial position. Also, the end of the silk was to be clamped to tighten the silk. However, the knot could not be tightened completely using this method. Therefore, to imitate the manual knotting process, the tension mechanism was added to imitate the hand through the tension coil, thereby completing the tension process. Artificial tensioning was considered as a way to work as the hand along the silk cake rotation tension so that the knot would slide along the silk cake until it was tightened. To achieve this, a line-blocking mechanism was designed using a pneumatic control system to make the node fixed on a horizontal line of the package. After loosening the transition coil, the length of the silk from the stop bar to the ring mechanism was fixed. Thereafter, the status of the silk was obtained by using the catenary equation, and the relevant parameters of the pick bar were appropriately determined. The



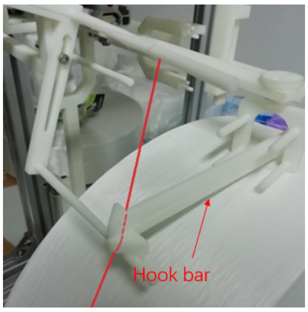
(a) Step 1: Clamp the wire



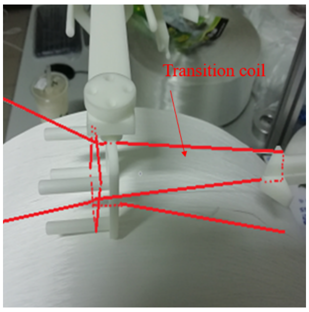
(b) Step 2: Rotate around the YOZ face



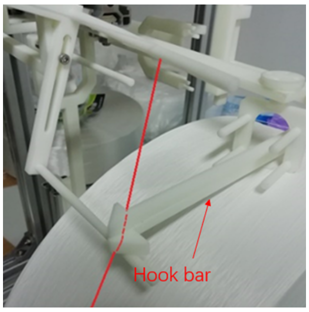
(c) Step 3: Node coil



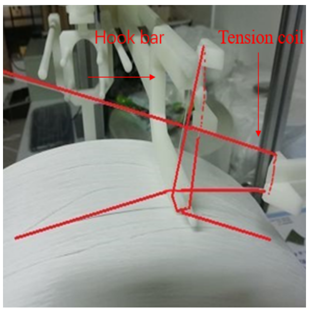
(d) Step 4: Hook the wire through the node coil



(e) Step 5: Form a transition coil

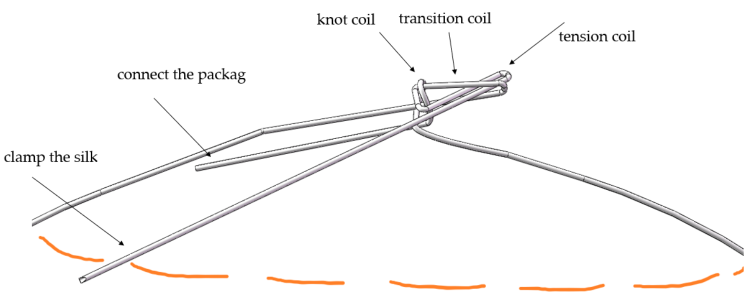


(f) Step 6: Hook the wire through the transition coil



(g) Step 7: Tension coil

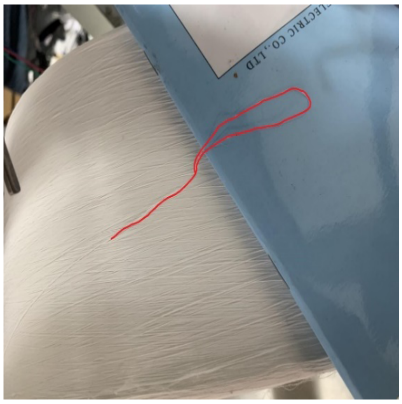
(h) Step 8: Tighten



(i) knot diagram

Fig. 2. Knotting process of the chemical fiber filament

(a) Man-made knot



(b) Machine-made knot

Fig. 3. Photographs of man-made and machine-made knots

schematic representation of the state of the yarn is shown in Figure 5. The manual knotting method was designed using SolidWorks software. The silk head was clamped using the clamping mechanism. This mechanism could also work along with the tension mechanism to complete the coil-tightening action. However, due to the requirement for the final formation, the knot could be placed closer to the package around the surface using the pick-silk mechanism provided with the tension coil. Finally, the storage action is completed by driving the storage bar rotation using a motor.

The schematic representations of the tension mechanisms are shown in Figure 6 and Figure 7. The tension mechanism was used for clamping the silk head, and the bar was stopped using the cylinder control so that the nodes were positioned along the horizontal line of the package. The pick bar comprises a multi-degree of freedom pick mechanism, which can be

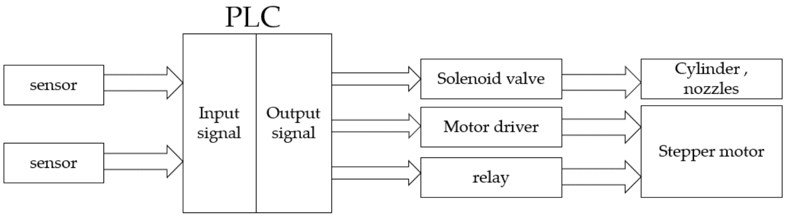


Fig. 4. Knotting control schematic diagram based on PLC [21]

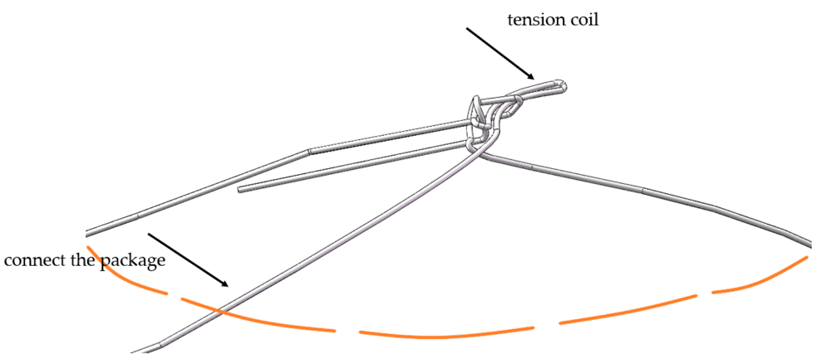


Fig. 5. Schematic representation of the state of yarn tension

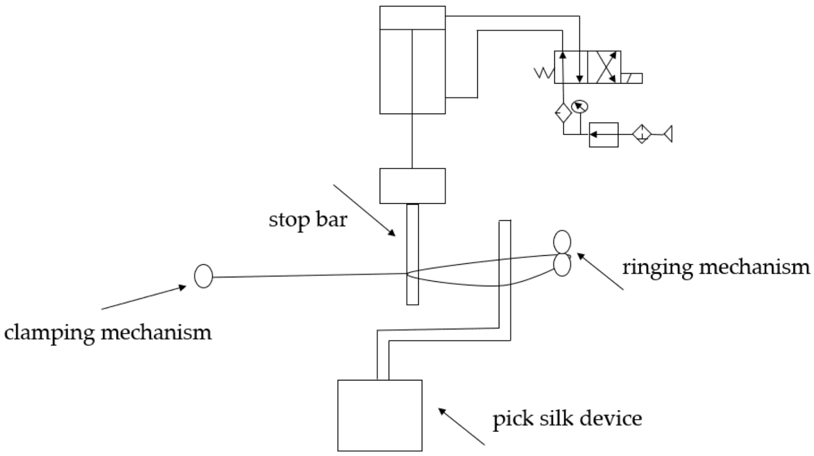


Fig. 6. Schematic diagram of the tension mechanism

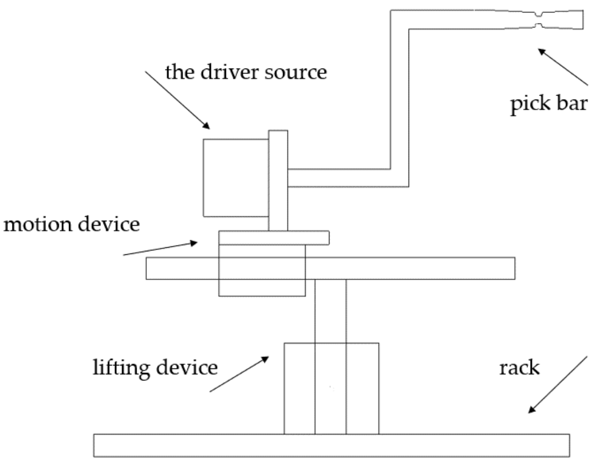


Fig. 7. Schematic diagram of the opening device

operated accurately and swiftly using an artificial operation. The quick, accurate, and dexterous characteristics significantly ensure the authenticity of the pick-silk. It was also observed that the efficiency of knots also improved with the automatic processing of the silk cake.

Silk is a flexible material and any point on the silk would be subjected to pull along the curve tangent direction without bending moment and torque. Therefore, the silk catenary equation was employed to determine the pick silk bar required to enter the best position. In the study of the kelp knotting principle based on the catenary theory, Li et al deduced the equation of unequal high catenary, and the corresponding stress diagram is shown in Figure 8.

$$\begin{cases} m+n=l \\ a(\cosh\frac{n}{a}-\cosh\frac{m}{a})=h_2-h_1=\Delta h \\ a(\sinh\frac{m}{a}+\sinh\frac{n}{a})=s \end{cases} \quad (1)$$

In Eq. (1), s refers to the chain length, m refers to the span between two points A and O, n refers to the span between two points B and O, l refers to the span between two points A and B, a refers to the coefficient of the equation system, and Δh refers to the altitude difference between two points A and B. In the original design, also referred to as the ring mechanism, the stop bar horizontal distance was taken as 90 mm. Δh refers to the ring mechanism and the stop bar vertical distance was taken as 30 mm. Furthermore, the length of the segment truncation was taken as s=105 mm, and the values of a, m, and n are obtained as shown in Eq. (2).

$$\begin{cases} a\approx 54.39 \\ m\approx 29.01 \\ n\approx 60.99 \end{cases} \quad (2)$$

The catenary equation is given in Eq. (3).

$$y=54.39*\cosh(\frac{x}{54.39})-54.39 \quad (3)$$

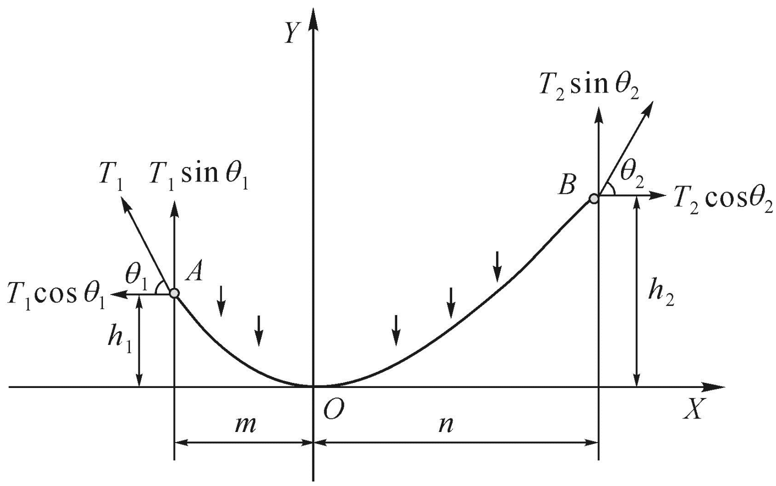


Fig. 8. Force diagram of catenary points at various heights [22]

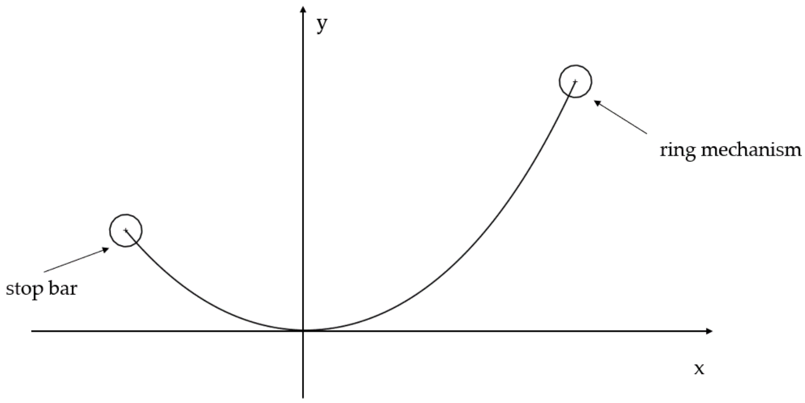


Fig. 9. Schematic diagram of the yarn state

POY	FDY	factor	Level			
			1	2	3	4
A	D	Tightening pulse (Piece)	22000	22300	22600	22900
B	E	Tightening speed /(r/s)	1	2	3	4
C	F	Ring size/mm	45mm	48mm	51mm	54mm

Table 1. Test parameters

The result of the curve is shown in Figure 9.

In addition to this, to allow the pick silk bar to pass smoothly through the lower half of the tension coil silk, the package was designed based on the silk state diagram and the relative position of the stop bar, with the final diameter of the pick silk bar measuring 5 mm. The diameter of the package measured 305 mm and the pick silk bar height measured 164 mm. The pick silk bar was rotated from the vertical state to about 14°, along the lower part of the tension silk. In order to leave a margin and to allow the pick silk bar to be as close to the package as possible, the pick silk bar height was adjusted to 168 mm. However, at the same time, the pick silk bar was also required to rotate from the vertical state angle between 10°and 20°. Finally, the knot was tested with the diameter of the pick silk bar set at 5 mm, the height at 168 mm, and the angle required for the rotation while passing through the tension coil at 15°.

3. Results

To verify the applicability of the tension device, the test was carried out on a homemade knotter test bench. It was observed that after the pick silk bar entered the tension coil, the silk needed to be driven by the motor at the storage bar to complete the tightening action. Also, the drive subdivision parameter was changed to 8, so that the motor rotated at a rate of 1600 pulses per cycle. The size of the ring could be adjusted by controlling the position of the pick silk bar after entering the tension coil. The test parameters in Table 1 show the pulse, tightening speed, and the ring size of the storage bar tightening. In order to conclude whether the knot was close to the surface of the package and to determine the success of knotting, each test was conducted 10 times. The final test results are shown in Table 2.

From the test results, it can be observed that the optimal parameters of POY and FDY are A3B1C3 and D1E1F1 respectively. Additionally, it can be seen that the ring size, tightening speed, and tightening pulse all have an impact on the knotting characteristics. The results thus demonstrate that the tightening pace should not be very high or rapid because that would cause the silk to wind itself around the pick silk bar. Additionally, it can be noted that this may be improved by making the rings larger, although doing so would likely interfere with later package recognition due to the rings' excessive size. Because FDY is a full draw yarn and POY is a pre-oriented yarn, the fiber is fully stretched during the tightening pulses, causing the pulse to be larger and the knot to be tightly packed.

4. Discussions

The knot test of two different packages of POY and FDY was carried out, and the relevant parameters were optimized. The analysis can be summarized as follows: the pick bar must be designed with a height of more than 164 mm to ensure smooth crossing of the coil. It was observed that when the height of the pick bar exceeded this, the range of the height was larger. However, the increase in the

No.	A	B	C	Number of knots (piece)	D	E	F	Number of knots (piece)
1	1	1	1	3	1	1	1	9
2	1	2	2	5	1	2	2	5
3	1	3	3	6	1	3	3	0
4	1	4	4	4	1	4	4	0
5	2	1	2	5	2	1	2	8
6	2	2	1	6	2	2	1	7
7	2	3	4	3	2	3	4	2
8	2	4	3	4	2	4	3	0
9	3	1	3	9	3	1	3	4
10	3	2	4	3	3	2	4	1
11	3	3	1	7	3	3	1	6
12	3	4	2	7	3	4	2	3
13	4	1	4	4	4	1	4	0
14	4	2	3	6	4	2	3	4
15	4	3	2	7	4	3	2	5
16	4	4	1	6	4	4	1	6

Table 2. test results and analysis

height of the pick bar would make the node coil deviate more from the package, and may result in loose knots. When the package was knotted, the orthogonal test was carried out, and it was observed that by increasing the pulse, the knot would be tightened and loosened at regular intervals. Moreover, it was found that as the tightening speed increases, the time duration required to form the knot decreases, however, the warping of the coil around the coil was easier when the speed of the coil was larger. Moreover, by controlling the angle of the pick bar rotation, the size of the formation coil could be controlled, and the size of the coil formed was associated with the tightening pulse. The optimal parameter of the POY that was selected for this work was found to be A3B1C3 and the optimal parameter of FDY was D1E1F1. Additionally, it was discovered through the analysis of the motion characteristics that the design of a fully automatic knotting mechanism might reduce the need for human involvement in the knotting procedure, enabling the chemical fiber industry to reach complete automation. The mechanical structure and timings of mechanical actions of various sections would be optimized provided that reliable checks of the functional requirements needed to improve the system's operating effectiveness were carried out. In addition to this, the knots on the silk car might produce multi-station knots by gradually diminishing the knotting mechanism. It is common knowledge that a gas source must be available when the mechanism uses a cylinder drive. As a result, if the gas source is unstable, the knotter mechanism may be impacted. With flexible bodies, even a small change in the gas supply can have a significant effect. Since the motor will be replacing the relevant drive, it must be chosen carefully to prevent later issues. In this work, a tension mechanism was designed and the key parameters were optimized. The key parameters were optimized based on the artificial knot design knotting mechanism and through the operation of the pneumatic system control mechanism. The optimization of key parameters was carried out to debug the final optimal parameters. Moreover, the tension mechanism was designed to meet the knot requirements, which include the formation of the knot according to the requirements of the factory which ensure that the formation of the knot is such that it will not be loosened in the follow-up movement process. Although there were reports of automation of manual knotting in the literature, the operating efficiency of the system had to be improved. It was found that the operating efficiency of the system could be improved by optimizing the mechanical structure and the mechanism execution timing of various parts provided that reliable checks of the functional requirements needed to improve the system's operating effectiveness were carried out. Nevertheless, this work also provides a theoretical as well as a practical foundation for further optimization of the knotting mechanism.

5. Conclusions

The precise objective of this work is to construct a fully automated knotter system platform while testing the knotting of coils of different sizes. The experimental results show that a coil size of 55mm is the most favourable for knotting by the knotting machine. The outcome also demonstrates that the developed automatic knotting machine can replace the manual knotting machine stably and the knotting can meet the usage requirements.

Author Contributions

Conceptualization, R.G.Z. and P.F; methodology, R.G.Z; software, P.F; validation, F.P. and Y.C.C.; formal analysis, F.P. and Y.C.C.; investigation, R.G.Z.; resources, Y.C.C.; data curation, R.G.Z.; writing—original draft preparation, R.G.Z.; writing—review and editing, F.P.; visualization, F.P.; supervision, F.P. and Y.C.C.; project administration, F.P.; funding acquisition, F.P. All authors have read and agreed to the published version of the manuscript.

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