Optimisation method for the quality of combed sliver

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ABSTRACT – REZUMAT

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The quality of the sliver is a key parameter for assessing the technical level of spinning equipment. As a critical machine in the spinning process, the sliver-quality optimisation system of the cotton comber is crucial for enhancing cotton sliver quality. Based on the process characteristics of cotton combers, this paper proposes a new non-real-time optimisation method for improving the evenness of combed slivers and verifies the feasibility of this method through experiments on combed slivers. Firstly, the paper introduces a new method for optimizing sliver quality. Secondly, online sliver quality data are collected and then processed through smoothing and correlation analysis to determine the periodic variations in sliver quality. Next, according to the principle of sliver evenness and the open-loop control system, a model is established between sliver quality variation and the middle roller speed. The periodic motion law of the middle roller is then determined. Experimental results show that the method, after non-real-time processing of sliver data, reduces the coefficient of variation (CV) of the sliver by 0.5%. Furthermore, a multi-stage speed control for the middle roller is proposed to replace the continuously variable speed control. This reduces the requirements and cost of the control system and still lowers the sliver CV by 0.38%. This proves that the method meets the combed sliver quality optimisation requirements. Finally, the impact of open-loop system delay time on non-real-time processing time during actual operation is analysed to further ensure the optimisation of roller speed regulation. This study provides a practical technical solution and a theoretical basis for online sliver leveling in the combing process.

Keywords: *non-real-time processing, open loop, comber, sliver, quality optimisation*

Metodă de optimizare a calității benzii pieptănate

Calitatea benzii fibrelor de bumbac reprezintă un parametru cheie pentru evaluarea nivelului tehnic al echipamentelor de filare. Fiind o mașină esențială în procesul de filare, sistemul de optimizare a calității benzii de fibre al mașinii de pieptănat bumbac este deosebit de important pentru îmbunătățirea calității benzii fibrelor de bumbac. Pe baza caracteristicilor procesului de pieptănare a bumbacului, lucrarea de față propune o nouă metodă de optimizare în timp real pentru îmbunătățirea uniformității benzilor pieptănate și verifică fezabilitatea acestei metode prin experimente efectuate pe benzi de bumbac pieptănat. În primul rând, lucrarea prezintă o nouă metodă de optimizare a calității benzii de fibre. În al doilea rând, datele privind calitatea benzii de fibre sunt colectate în timp real și apoi prelucrate prin metode de netezire și analiză de corelație pentru a determina variațiile periodice ale calității benzii de fibre. În continuare, pe baza principiului uniformității benzii de fibre și a sistemului de control în buclă deschisă, se elaborează un model care leagă variația calității benzii de fibre de viteza cilindrului central. Se determină apoi legea mișcării periodice a cilindrului central. Rezultatele experimentale arată că această metodă, după prelucrarea în regim non-real-time a datelor privind banda de fibre, reduce coeficientul de variație (CV) al benzii cu 0,5%. În plus, se propune un control al vitezei în mai multe trepte pentru cilindrul central, în locul controlului continuu al vitezei. Acest lucru reduce cerințele și costurile sistemului de control și scade în continuare coeficientul de variație al benzii cu 0,38%. Acest lucru demonstrează că metoda îndeplinește cerințele de optimizare a calității benzii pieptănate. În final, se analizează impactul timpului de întârziere al sistemului în buclă deschisă asupra duratei de procesare în regim non-real-time în timpul funcționării efective, pentru a asigura și mai mult optimizarea reglării vitezei cilindrilor. Acest studiu oferă o soluție tehnică practică și o bază teoretică pentru optimizarea online a benzii în procesul de pieptănare.

Cuvinte-cheie*: prelucrare în regim non-real-time, buclă deschisă, mașină de pieptănat, banda de fibre, optimizarea calității*

INTRODUCTION

The textile industry, as a pillar industry of the global manufacturing system, has a continuous demand for improving quality and standards [1]. The quality of the spinning process directly determines the quality of subsequent textiles [2], and sliver quality is the basis of yarn quality, which largely determines the development of the textile industry. Current sliver quality optimisation generally refers to self-leveling control on carding and drawing machines. In actual production, however, the impact of the combing process on sliver quality cannot be ignored [3]. However, the open-loop, closed-loop, and mixed-loop self-levelling control methods used on carding and drawing machines are not suitable for cotton combers, which have complex structures, limited sensor installation positions, and a long distance from the drafting zone. In recent years, with the rapid development of technologies such as digital twins [4] and artificial intelligence [5], new technological support has been provided to solve this problem. Therefore, further strengthening research on quality optimisation methods for combed cotton sliver and integrating the latest intelligent and digital technologies is of great practical significance for improving overall spinning quality and promoting industry development.

Current optimisation methods for sliver quality mainly focus on the self-leveling control methods on carding and drawing machines [6]. Wang et al. [7] set short closed-loop control at the feeding roller and the doffer to optimise sliver quality through speed regulation. Li et al. [8] conducted a detailed analysis of the delay time to enhance yarn optimisation. Wang et al. [9] researched the closed-loop control of carding machines and improved the system's anti-interference ability by changing the self-levelling controller. Domestic and foreign experts have also researched and analysed the control of the loading mixing ring on the carding machine [10]. Although optimisation has advanced, shortcomings in control and cost remain challenging to resolve. At present, concave-convex rollers are generally used on drawing frames to detect sliver quality, after which the speed of the drafting roller on the drawing frame is adjusted to achieve sliver evenness. Jie et al. [11] used concave-convex rollers to detect the sliver quality earlier and then optimised the sliver quality by controlling the speeds of the rear and middle rollers. Hongliang et al. [12] set up two detection devices between the drafting components and behind the drafting area, adjusting the speeds of the front and rear rollers to achieve uniform yarn quality. Some experts have also applied the mixed-loop control method on the drawing frame [13], which can ensure optimisation, but the economic cost is still high. Based on the research on drawing machines by these experts, the above methods are all real-time feedback optimisation, in which detection and adjustment are carried out simultaneously. By detecting and adjusting the drafting roller at the same time, the optimisation of sliver quality can be achieved. Although open-loop control has been well optimised, delay still significantly affects the real-time optimisation of yarn. Unlike the aforementioned self-levelling control method, this paper introduces a novel non-real-time optimisation approach that enhances cotton sliver quality by acquiring and processing quality data, analysing its inherent patterns, and subsequently optimising the roller speed.

This paper proposes a novel method for optimizing sliver quality in combing machines. First, cotton sliver quality data are smoothed and correlation-analysed to eliminate interference, then the DS-MMFI algorithm is used for cyclic data collection and error analysis. Based on momentum conservation and the relationship between sliver weight and count, a mathematical model linking middle roller speed to sliver quality is established. This model reveals periodic behaviour and is validated experimentally.

Furthermore, by analysing delayed data and the relationship between roller speed and sliver weight variations, the motion cycle is deduced, and sliver quality is optimised, reducing non-uniformity by 0.5%. Considering the complexity and cost of servo control, a multi-stage speed adjustment method is proposed as an alternative to continuous variable speed control, with experiments showing a 0.38% reduction in non-uniformity. Finally, analysis of control delay indicates that, with an optimal delay, the middle roller's periodic motion can be more precisely synchronised with the drafting cycle, further refining the process. Non-real-time processing provides ample time for data analysis and delay evaluation, reducing real-time errors, while the periodic multi-stage speed control lowers system demands and offers theoretical support for future cotton sliver quality optimisation.

OPTIMISATION METHOD FOR SLIVER QUALITY

Sliver quality optimisation is achieved by adjusting the speed of the middle roller in the drafting zone of the comber. Due to the complex mechanical transmission of the comber, the front roller is tightly integrated with the feeding system, while the rear roller cooperates with the output system. In contrast, the operation of the middle roller is relatively independent, exerting minimal influence on the preceding and succeeding processes. Moreover, as the front and rear rollers determine the overall drafting ratio, and with the rear roller imposing higher motor requirements, the optimisation range and fluctuation of the middle roller speed are relatively limited. Therefore, adjusting the middle roller speed can reduce interference with the operation of other components. The sliver quality optimisation method is shown in figure 1 and is different from traditional self-leveling control. This method adopts a non-real-time open-loop control method. The sliver quality data is processed over time after being detected by the sensor. After obtaining the sliver quality cycle law, the corresponding motion law of the middle roller is obtained, and the sliver quality is adjusted by adjusting the middle roller's speed.

Based on the specific analysis shown in figure 1, the drafting components are operated according to the original draft ratio, and the detection device is installed at the sliver outlet during the sensor detection stage, and before quality optimisation adjustments, to reduce the impact on the original structure of the comber. After obtaining the sliver quality cycle through data processing, the model relating the sliver quality and the middle roller speed is combined to obtain the periodic motion law of the middle roller. At the same time, the motion law of the middle roller is approximated in multiple stages to reduce control system requirements and ultimately achieve sliver quality optimisation.

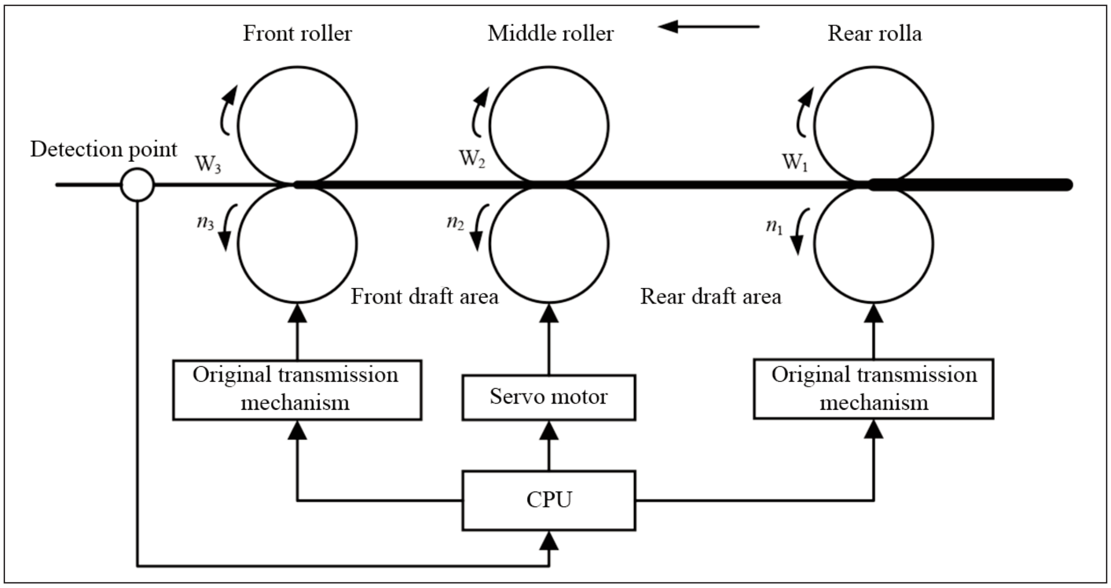

Fig. 1. Diagram of the evenness quality optimisation method: W_1 – input sliver quantity; W_2 – quantification of cotton sliver after rear zone stretching; W_3 – output sliver quantity; n_1 – front roller speed; n_2 – middle roller speed; n_3 – rear roller speed

DATA PROCESSING

Due to the complexity of the online detection environment, firstly, smoothing and correlation preprocessing are performed on the sliver quality data. Subsequently, a period extraction algorithm is used to determine the period of sliver quality data, and error analysis is conducted to ensure the accuracy of the extracted period, laying the foundation for subsequent sliver quality optimisation.

Data preprocessing

Data preprocessing mainly ensures quality by eliminating interference such as noise. Before adjusting the speed of the middle roller, it is necessary to predict the sliver data pattern and determine the middle roller speed pattern. Given the actual drafting speed and machine structure, it takes about 1–3 seconds for the sliver to travel from the drafting zone to the detection position. Therefore, a 10-second sampling time is set to collect sliver quality data, as shown in figure 2.

The sliding average method [14] is used to complete the smoothing process. The data obtained after processing is recorded as follows, based on the moving average analysis:

$$\begin{cases} m(1) = \dfrac{[4u(1) + u(2)]}{5} \\ m(t) = \dfrac{[u(t-1) + 3u(t)u(t+1)]}{5}, \; 1 < t < n \\ m(n) = \dfrac{[u(n-1) + 4u(n)]}{5} \end{cases} \tag{1}$$

Where $\{u(t)\}$ is the dataset, $t \in Q$, Q is a positive integer.

After completing the data smoothing process, the data shown in figure 3 shows a clear trend with significantly reduced random interference. Next, the correlation of the data is analysed to remove small fluctuations and improve the accuracy in obtaining cycles. The autocorrelation function of the discrete sequence mentioned above is

$$R_{(k)} = \lim_{N\to\infty} \frac{1}{2N+1} \sum_{h=-N}^{N} u(h)u(h-k) \tag{2}$$

where k are the delay points. The sample size N of the time series is 1000.

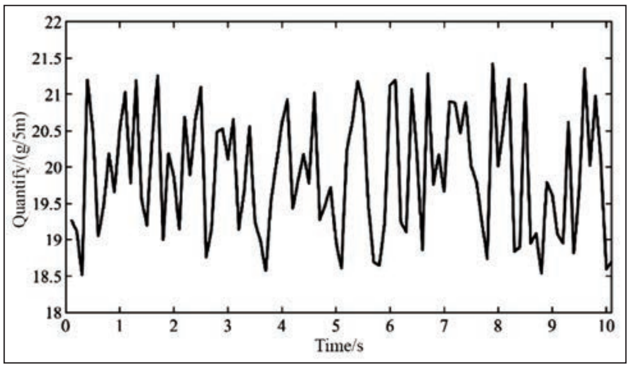

Fig. 2. Evenness quality data

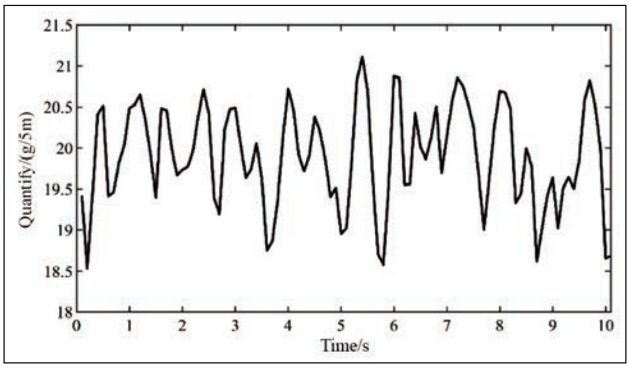

Fig. 3. Smoothed data

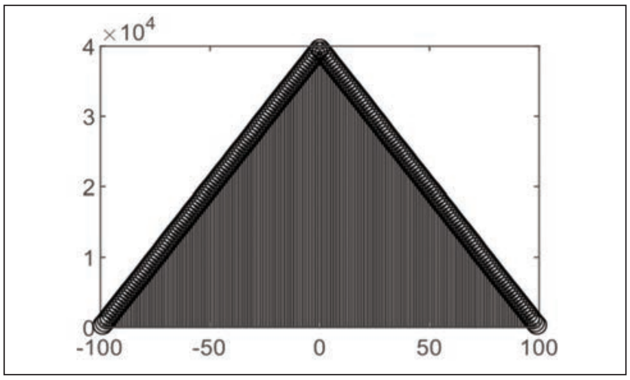

Fig. 4. Data autocorrelation analysis results

Autocorrelation reflects the similarity between the data and itself after a specified delay [15]. Figure 4 shows the sequence autocorrelation results, and the data can then be autocorrelated to further extract the data period.

Cycle extraction

Currently, the most frequently used periodic sequence data mining algorithms include the Max Miner, MAFIA, FP Max, and MMFI algorithms. The MMFI algorithm has the highest extraction efficiency and mining frequency, while analysis of sliver quality data focuses on its variation trend [16]. Therefore, the DS-MMFI algorithm based on variable periods is most suitable. This method avoids sequence loss due to strict cycle start and end restrictions. The most representative part of the mined sliver quality data, determined through frequent mining, is the periodic component, which is approximately 1.6 seconds long. Finally, to minimise the error in extracting periodic data, it is necessary to average the data from the first cycle with other cycles. The resulting data cycle is shown in figure 6, and the error for the corresponding period is shown in figure 7. According to the error analysis, the accuracy and precision of the extracted data cycle are relatively high, demonstrating that the sliver quality data exhibit distinct periodic patterns and high cycle similarity.

Optimisation of the middle roller motion law

After obtaining the periodic characteristics of the sliver data, it is necessary to establish a functional model between the rotational speed of the middle roller and the sliver quality. From this model, the corresponding periodic motion pattern of the middle roller can be derived to optimize sliver quality.

According to the law of conservation of momentum in the actual drafting process:

$$v_1 \times W_1 = v_2 \times W_2 = v_3 \times W_3 \qquad (3)$$

where v_1 is the speed of the sliver at the rear roller, v_2 – the speed of the sliver at the middle roller, and v_3 – the speed of the front roller at the sliver.

Based on the quality optimisation method diagram in figure 1, the detection point is set behind the drafting component, and the middle roller speed is adjusted by detecting the weight change of the drafted sliver. The control principle diagram is shown in figure 7. First, the sliver dry weight is set according to the process requirements. At this point, the dry weight should reach the standard value h_0, but there may be a deviation Δh between the actual dry weight and the standard value. After processing the delay time, the controller determines the roller speed change based on the dry weight change, and the speed change is set to Δn. Under this condition, the sliver quality is optimised.

A mathematical model must be established before verifying the above control method. The evenness model of the comber is established by ensuring that the input fibre amount per unit time equals the sum of the output fibre amount and the fibre amount inside the comber [17]:

$$Q_{in}(t) \times (1 - \eta) = Q_{out}(t) + Q(t) \qquad (4)$$

where $Q_{out}(t)$ is the amount of fibre output per unit time, g/min; $Q_{in}(t)$ – the amount of fibre input per unit time, g/min; $Q(t)$ – the fibre quantity inside the comber, g/min; η – the cotton drop rate.

Equation 4 represents the basic principle of evenness. For analytical convenience, the cotton drop rate η is set to zero, and the fibre quantity $Q(t)$ inside the drafting zone remains unchanged:

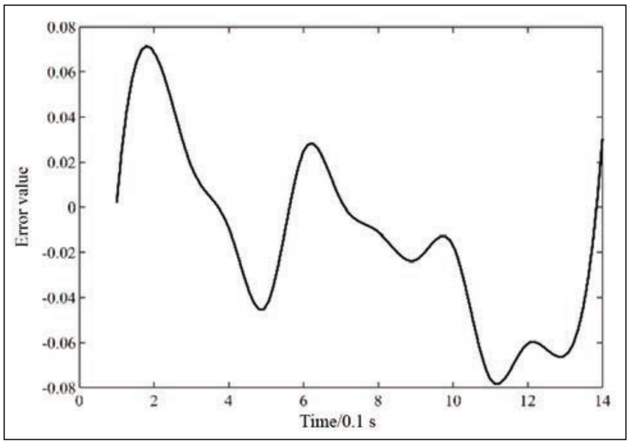

Fig. 5. Periodic data

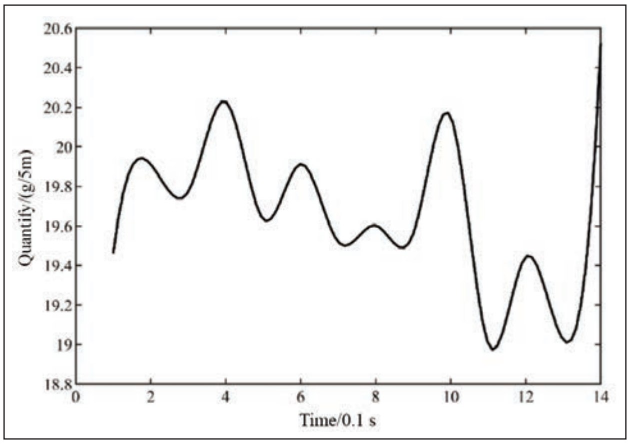

Fig. 6. Data error

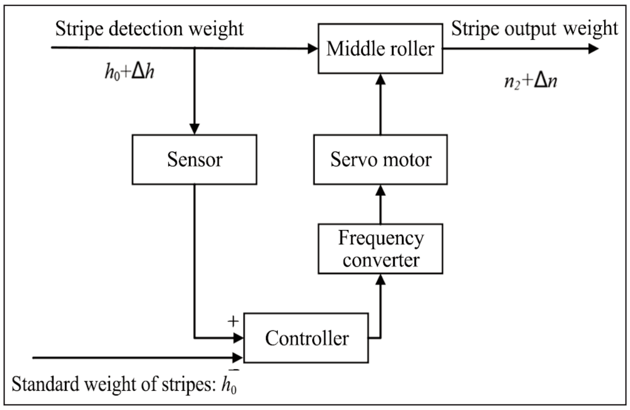

Fig. 7. Control schematic diagram of the quality optimisation method

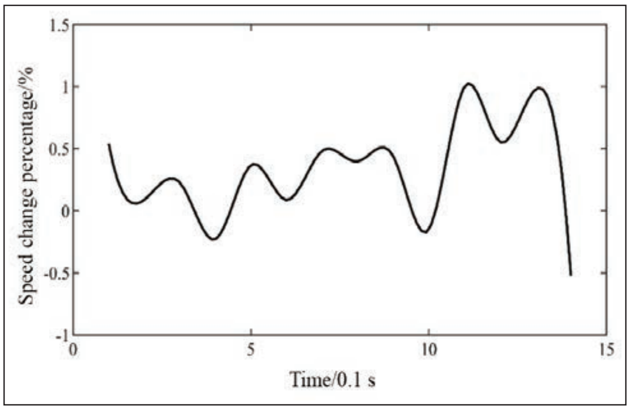

Fig. 8. Periodic variation of middle roller rotational speed

$$Q_{in}(t) = Q_{out}(t) + Q(t) \qquad (5)$$

Selecting sliver density as the detection target and adjusting the middle roller speed have little impact on rear drafting, which can be ignored. Therefore, only the section from the middle roller's input to the front roller's output is considered. Accordingly, the amount of fibre input per unit time can be expressed as:

$$Q_{in}(t) = h_0 = \rho_1 V_1 \qquad (6)$$

where ρ_1 is the density of the input sliver of the middle roller, g/cm^3; h_0 – the input sliver weight; V_1 – the corresponding unit volume of the input sliver, m^3.

The linear speed at each roller refers to the magnitude of the surface speed at that point. The conversion relationship between it and the middle roller speed is:

$$v_{in} = \pi D n_2 \qquad (6)$$

where v_{in} is the original input speed of the middle roller, m/min; n_2 – the middle roller speed, m/min; D – the diameter of the middle roller, mm.

The purpose of drafting is to ensure that the weight of the output sliver remains unchanged. Therefore, $Q_{out}(t)$ can be considered a constant value under ideal conditions. If the output sliver weight is equal to the original $Q_{out}(t)$ before and after changing the middle roller speed and satisfies the momentum conservation theorem in equation 3, then

$$v_{out} \cdot Q_{out}(t) = v_{in} \cdot Q_{in}(t) = h_0 \cdot v_{in} = (h_0 + \Delta h) \cdot (v_{in} + \Delta v) \qquad (7)$$

where $v_{in}(t)$ is the speed of the input bar, m/min; $v_{out}(t)$ – the speed of the output bar, m/min.

By substituting the relationship between rotational speed and linear speed in equation 7 into equation 8 for simplification:

$$\Delta n = -\frac{n_2}{1 + \dfrac{h_0}{\Delta h}} \qquad (9)$$

Equation 9 is the quality optimisation model for the middle roller speed, and the drafting quality optimisation can be completed based on this. By combining the extracted sliver data period with the relationship in equation 9, the change in the middle roller speed can be determined, as shown in figure 9. Based on this, the middle roller only needs to adjust its speed according to the percentage change shown in figure 8 to optimise the sliver quality.

EXPERIMENTATION

To verify the effectiveness of the non-real-time open-loop control method in regulating sliver quality, the modification experiment was conducted on the AHC601 combing machine produced by Henan Haochang Combing Machine Joint-Stock Co., Ltd. The drafting device used in this comber is a 3-over-3 roller drafting system, with an experimental speed of 350 nips per minute. The control system uses Delta's ECMA-C20604RS servo motor, ASDA-B2-0421-B driver, and Omron's CP1H controller. The raw materials used in the experiment were from the same batch of cotton, and their main fibre characteristic parameters are as follows: fibre length of 26.5–27.3 mm, fineness of 148–153 mtex, and maturity of 0.80–0.83.

Figure 9 shows the schematic control diagram for the quality optimisation method. First, the detected sliver data is input into the system for time-series processing. The delay time is initially set to 3 seconds, which is combined with the travel time of the sliver from the drafting position to the detection point. After obtaining the sliver quality data cycle, the model describing the relationship between sliver weight and middle roller speed is used to derive the periodic motion law of the middle roller speed, thereby optimising the sliver quality. The first "Fcn" module in the figure corresponds to the functional relationship of equation 9. Because this relationship links the variation in sliver length to the variation in middle roller speed, it is necessary to subtract the rated quantitative value h from the data, with a size of 20 g/5 m. Within the set 3-second period, the analysis of the proportion of changes in the middle roller speed in equation 9 is completed, and the variation law of the middle roller motion is obtained. This computed variation is then added to the original constant roller speed n to obtain the optimised roller speed law. After the unit conversion of the second "Fcn" module, the final sliver weight data is obtained from the output module.

After 10 sets of repeated experiments, the optimisation scheme reduced the sliver CV% by approximately 0.5%. However, frequent high-speed changes in roller speed are undesirable in the actual production process. Therefore, a multi-stage motion method is adopted here instead of frequent variable speed motion. From the actual impact data trend in figure 9, it can be set as a three-stage speed change, and then the intermediate value of the three-stage speed change can be obtained. At this point, the three-stage speed change can be identified as a proportional change in the speed magnitude centred on the original roller speed, as illustrated in figure 10.

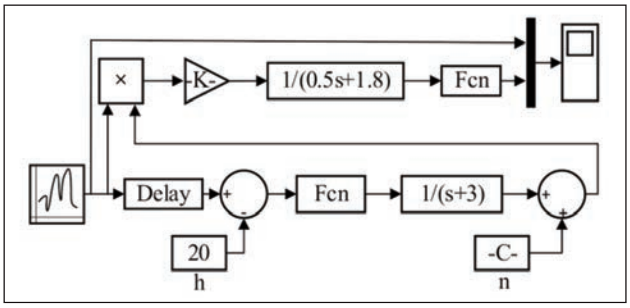

Fig. 9. Principle of quality optimisation method

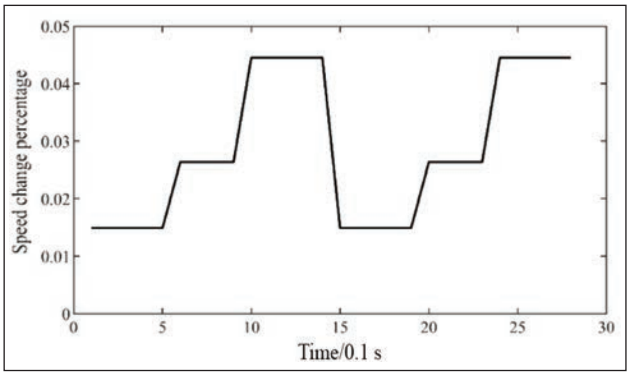

Fig. 10. Three-stage periodic change in speed

To verify the uniformity improvement effect of the multi-level motion method, experiments were conducted using the same equipment and identical production conditions as those of the aforementioned optimisation method. The motion law was directly applied to the middle roller through a servo motor, and then the sliver data obtained after the quality optimisation method was collected online. Figure 11 shows the comparison of effects before and after the application. After 10 sets of repeated experimental analyses, it was found that the sliver CV% was reduced by about 0.38%. Although this method is not as effective as the frequent variable speed method, it significantly reduces costs and implementation difficulties.

ANALYSIS AND DISCUSSION

There is a delay in the open-loop adjustment method behind the machine. If the delay time could be better determined and set in the control system, it would inevitably improve the cotton sliver quality. The following is an analysis of the delay time.

After a processing period, the total hysteresis τ_0 of the rear open loop can be expressed as:

$$\tau_0 = \tau_1 - \tau_1' \qquad (10)$$

where τ_1 is the time from the rear detection point to the variable speed draft point, and τ_1' – the time taken for the detection point to change speed from the open-loop system to the central roller.

One key aspect of an open-loop system is to determine the delay time τ_0. The first step is to establish a mathematical model of the control system, as shown in figure 12.

Under ideal conditions, the sliver satisfies the momentum conservation principle before and after drafting, so:

$$v_2(t)W_2(t) = v_1(t)W_1(t) \qquad (11)$$

where v_1 is the sliver speed at the front roller, m/min; v_2 – the sliver speed at the middle roller, m/min; $W_2(t)$ is the quantitative value of the sliver before this period.

After a time interval τ_2, the sliver reaches a speed change point and begins drafting. At this point, $W_2(t)$ can be regarded as the quantitative value of the sliver before this period, so $W_2(t) = W_3(t - \tau_2)$. However, the actual t is unknown, and its value is set to τ_2'. Then, from equation 11:

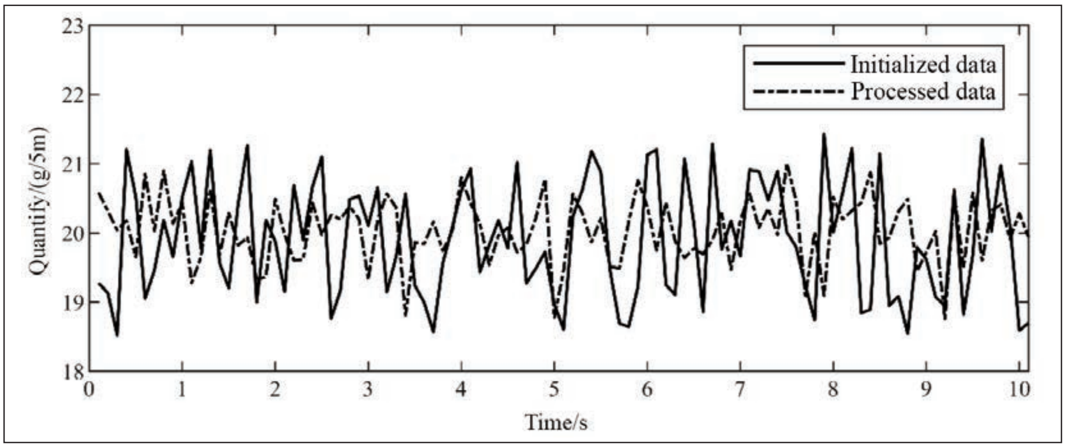

Fig. 11. Comparison of sliver quality before and after optimisation

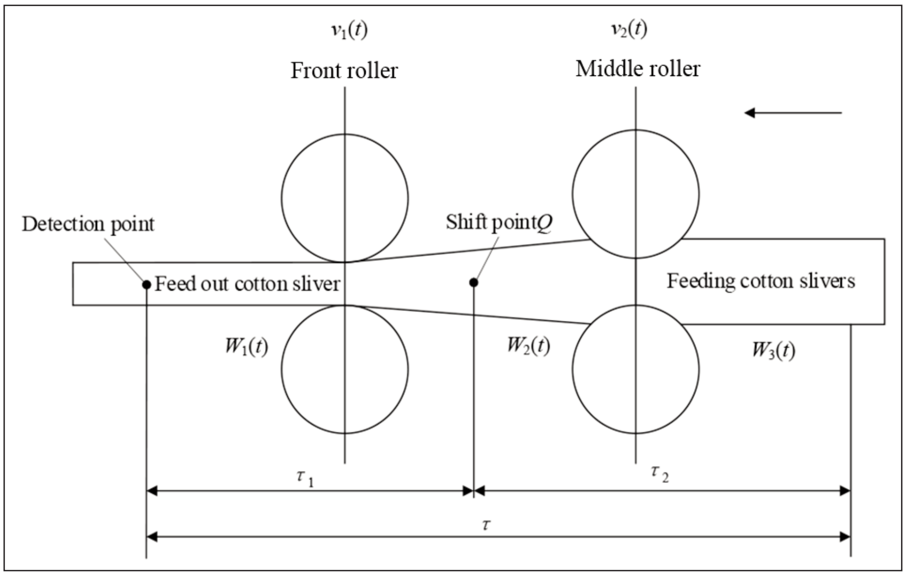

Fig. 12. Control system mathematical model

$$W_1(t) = \frac{v_2(t)W_2(t)}{v_1(t)} = \frac{v_2(t)W_2(t)}{v_2(t)W_3(t-\tau_2')} = W_1(t)\,\frac{W_3(t-\tau_2)}{W_3(t-\tau_2')} \tag{12}$$

If the sliver quantity of the detection point is $W_0(t)$, which can also be regarded as $W_1(t)$ after a time interval τ_2, then:

$$W_0(t) = W_1[t-(\tau-\tau_2)] = W_1(t+\tau_2-\tau) = W_1(t)\,\frac{W_3(t-\tau)}{W_3(t-\tau+\tau_2-\tau_2')} \tag{13}$$

When the delay time given by the system is equal to the actual delay time, the sliver quantity is output at the ideal set value. According to figure 12, the delay distance L in the actual drafting process refers to the distance between the detection point and the middle roller group. While the sliver passes through L, the draft ratio of the drafting zone remains unchanged, and the delay time can be determined as a fixed value under ideal conditions based on the correlation between the data.

The output cotton sliver quantity $W_1(t)$ and the input cotton sliver quantity $W_3(t)$ are two random processes with different time states. Since they belong to a unified system and are governed by certain deterministic factors, an internal connection exists between them, which meets the basic conditions for autocorrelation analysis. If its autocorrelation function is $R_W(\tau_3)$, then

$$R_W(\tau_3) = E[W_3(t)\,W_0(t+\tau_3)] = E\left[W_3(t)\,W_1(t)\,\frac{W_3(t+\tau_3-\tau)}{W_3(t+\tau_3-\tau+\tau_2-\tau_2')}\right] \tag{14}$$

where τ_3 is the random correlation time between the input and output cotton sliver quantification.

From equation 14, it can be seen that there is $\tau_3' = \tau$, and at this point, the autocorrelation function $R_W(\tau_3)$ reaches a maximum value. Because the combed sliver is the research object of this article, the distance of the sliver from the input point to the speed change point is small and can be approximately ignored during the actual drafting process.

Therefore, the calculation of the delay time is transformed into a calculation of the time-dependent variable in the autocorrelation function between the input and output sliver quantities. The delay time of the open-loop control method can be obtained by analysing the correlation between input and output cotton sliver quality and combining it with its autocorrelation function.

CONCLUSIONS

This paper proposes a non-real-time open-loop control method for optimising the evenness of slivers in a cotton comber. Online quality data are collected, smoothed, and analysed for correlation, and error analysis is conducted using the DS-MMFI algorithm. A mathematical model linking roller speed and sliver weight is established, and a multi-stage speed regulation strategy is employed to adjust the drafting ratio, thereby achieving effective sliver quality optimisation. Experimental results show that when frequent speed adjustments were applied via a servo motor, the CV value of the sliver decreased by 0.5%, whereas under multi-stage speed control, the CV value decreased by 0.38%. These findings demonstrate that the periodic motion of the middle roller under multi-stage speed-control can not only effectively improve sliver evenness but also provide cost advantages, thereby confirming the feasibility of achieving online quality optimisation in cotton combers. Moreover, correlation analysis between sliver quality input and output data further reveals the motion law of the middle roller, enabling a more accurate correspondence to the drafting cycle of sliver quality and thus enhancing the optimisation effect.

However, the control strategy proposed in this study primarily targets short-term sliver evenness by modulating the middle-roller speed in the rear drafting zone. Because short fibre content, neps, and sliver weight per meter are only weakly affected by adjustments in the rear drafting zone, they were not considered in this study. Nevertheless, these metrics are critical for evaluating overall yarn quality and subsequent spinning performance. Future work will systematically investigate these key quality parameters to establish a more comprehensive quality optimisation framework.

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