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**ОПТИМИЗАЦИЯ ГЕОМЕТРИИ ТРЕУГОЛЬНИКА КРУЧЕНИЯ
И СИСТЕМЫ ВЫТЯЖКИ ДЛЯ ПОВЫШЕНИЯ КАЧЕСТВА ПРЯЖИ
В КОЛЬЦЕВОМ ПРЯДЕНИИ**

**OPTIMIZATION OF TWIST TRIANGLE GEOMETRY AND DRAFTING SYSTEM
FOR ENHANCED YARN QUALITY IN RING SPINNING**

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В статье рассматриваются структурные и динамические параметры геометрии треугольника кручения и системы вытягивания в процессе кольцепрядения с целью повышения качества пряжи и снижения частоты обрывов. Основной задачей является экспериментальная проверка эффективности различных конфигураций зажимов и наклонов вытягивающей системы на кольцепрядильной машине FA-516 при использовании хлопковых волокон. В ходе экспериментов с применением стандартных Polaris и опытных зажимов достигнуто снижение обрывов пряжи до 40% и увеличение относительной прочности на 11,5%. Структурная деформация, распределение кручения и динамика натяжения анализировались через дифференциальные уравнения движения и модели напряжений и деформаций. Изменение геометрии треугольника вытягивания и добавление стабилизирующих элементов, таких как упругие рычаги и конические пружины, способствовали улучшению консолидации волокон, оптимизации трения в зоне формирования пряжи и стабилизации подачи кручения при различных угловых скоростях. Результаты направлены на развитие новых конструкций устройств форми-

рования пряжи, повышающих производительность и однородность продукции. Даны рекомендации по выбору оптимального наклона вытягивания и геометрии треугольника кручения для обеспечения максимальных прочностных характеристик. Предложена конструкция усовершенствованной вытягивающей системы с повышенной эффективностью.

This study investigates the structural and dynamic parameters of the twist triangle and drafting system in ring-spun yarn production to enhance yarn quality and reduce breakage rates. A core objective is the experimental validation of clip configurations and drafting inclinations on the FA-516 ring-spinning machine using natural cotton fibers. Advanced analysis of fiber movement, twist propagation, and drafting system deformation was conducted through theoretical modeling and graphical simulation using Maple software. Experimental comparisons involving standard, Polaris, and prototype clips demonstrated up to 40% reduction in yarn breakages and an 11.5% increase in relative breaking strength. Structural deformation, twist distribution, and tension dynamics were analyzed via differential motion equations and stress-strain models. Improved drafting geometries and tension-stabilizing components such as elastic levers and conical springs proved effective in consolidating fibers, optimizing friction in the yarn formation zone, and stabilizing twist input across angular velocity parameters. This research contributes to the development of innovative yarn-forming systems, enabling higher productivity and yarn consistency. Recommendations include precise drafting inclination and optimized twist triangle configuration for maximum tensile properties and uniformity. The study concludes with the development of a modified drafting system design yielding superior spinning efficiency.

Ключевые слова: кольцепрядение, треугольник кручения, обрывы пряжи, система вытягивания, консолидация волокон, геометрия прядения, зажимы Polaris, прочность пряжи, текстильная механика, моделирование натяжения.

Keywords: ring spinning, twist triangle, yarn breakage, drafting system, fiber consolidation, spinning geometry, Polaris clips, yarn strength, textile mechanics, tension modeling.

Scientific research is being conducted globally to improve modern, digitized, and automated equipment and technologies that enable rapid changes in the quality, quantity, and range of yarn and fabric products on the global market. Particular attention is given to enhancing yarn quality, developing efficient systems for improving the quality and competitiveness of ring-spun yarns, and introducing high-performance equipment and technologies in production plants. This includes measurement and control instruments, as well as improvements in the structural components of spinning machines.

Research efforts focus on spinning both natural and synthetic fibers and manufacturing

knitted products in several priority directions: Enhancing productivity and yarn quality on existing ring-spinning machines, with spindle speeds reaching 25,000–30,000 revolutions per minute, digitizing and automating spinning and fabric production processes, developing technologies for producing yarns and fabrics with advanced non-material properties, defining optimal parameters to improve yarn quality on ring-spinning machines, producing yarns of various grades, predicting yarn composition, structure, and quality indicators, improving yarn appearance and reducing irregularity by expanding the technological capabilities of spinning machines and using yarn production mechanisms.

In recent decades, ring spinning technology has undergone substantial evolution, becoming the cornerstone for high-quality yarn production used in both woven and knitted textile applications. Despite advancements, conventional ring spinning still suffers from several issues including yarn hairiness, non-uniform twist distribution, and frequent yarn breakages. One critical structural region influencing these drawbacks is the twist triangle—a geometric zone formed between the front drafting rollers and the yarn take-up point where twist is imparted.

In this triangle, not all fibers receive equal twist, causing some to remain loose and misaligned, which leads to increased hairiness and reduced yarn strength. Compact spinning systems, as an enhancement to traditional methods, were introduced to minimize the twist triangle by aligning fibers more effectively within the yarn body. The optimization of drafting geometry and twist triangle formation has thus become central to improving yarn quality and performance.

Several researchers have addressed the twist triangle problem from various scientific angles. Chen et al. applied finite element modeling to analyze fiber tension and displacement dynamics within the twist triangle, revealing that controlled geometry significantly enhances fiber consolidation [1]. Meanwhile, Kim et al. demonstrated that tension regulation through balloon control devices reduced hairiness and improved tensile uniformity [2]. Additionally, Li et al. used digital image processing techniques to analyze twist propagation and fiber orientation within the triangle, suggesting a strong correlation between triangle height and mechanical yarn properties [3]. These findings provide a foundation for further experimental studies, including the current work, which focuses on evaluating the structural behavior of cotton yarns in relation to twist triangle geometry, drafting inclination, and tension stabilization mechanisms.

Machinery manufacturers like Zinser, Rieter, and Suessen have developed systems such as Air-Com-Tex 700, K44 Com 4, and Elite, respectively, which facilitate the compact spinning process. These technologies optimize yarn characteristics while maintaining high productivity [1, 6...8].

Based on research analysis, research objectives have been defined. According to it, the objective of the study is to reduce yarn breakage and improve quality indicators by enhancing structural components and adjusting the drafting system parameters, based on the analysis of yarn drafting processes on ring-spinning machines.

During the study, it is analyzed that the spinning techniques and processes, the current state of spinning technology, yarn breakages on spinning machines, and the structure of machine components, specifically clips. The goal is to improve yarn quality by reducing breakages. The function of the clips is to reduce the front roller pressure, ensure the orderly movement of fibers, and decrease linear density irregularities in the yarn. During experiments, clips of different sizes were attached to the middle rollers of ring-spinning machines to study their impact on yarn quality and breakage rates (see Figure 1).

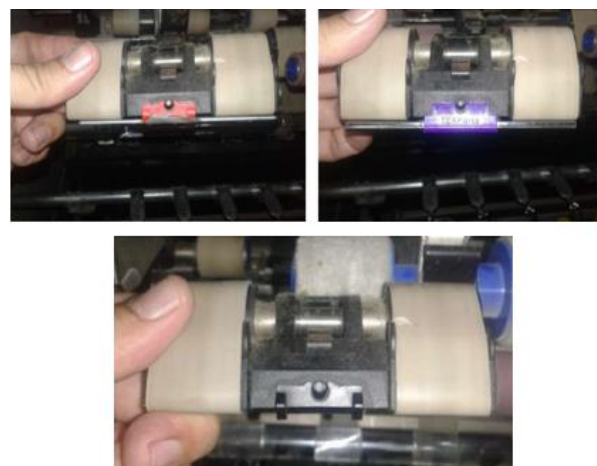


Fig. 1

The analysis showed that compared to standard factory clips:

Polaris brand clips reduced yarn breakage by 40%;

Experimental clips reduced it by 23%.

These improvements significantly contribute to the productivity and quality of yarn.

A ring-spinning machine of type FA-516 was installed at the factory, with 516 spindles per machine. Given that the experiments were repeated 10 times, the average number of yarn breakages per hour per machine was as follows:

With standard clips: 174 times (100%);
 With Polaris clips: 103 times (60%);
 With experimental clips: 135 times (77%)
 (see figure 2).

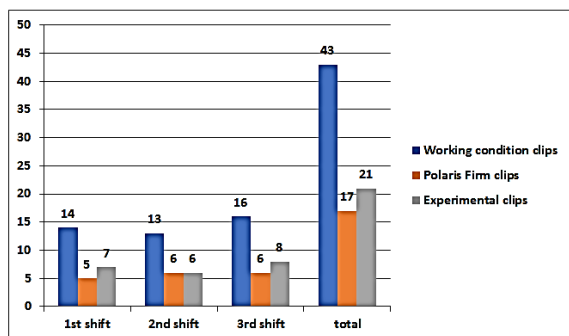


Fig. 2

When scaled to all machines in the facility, these differences become even more significant.

The experiments also showed an improvement in yarn characteristics along with the reduction in breakage. During all tests, the number of thin places, thick places, and the relative breaking strength showed noticeable improvement (see Figures 3).

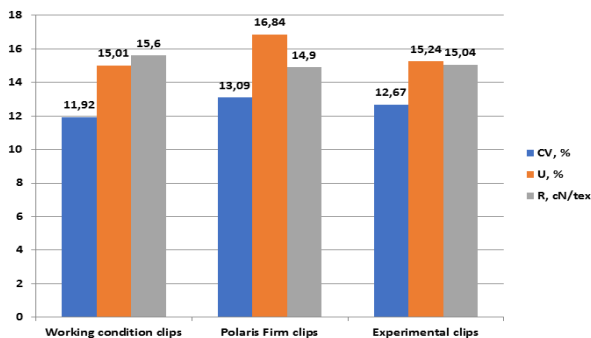


Fig. 3

As shown in the above figures, the prototype wire clip designed for the experiments reduced yarn breakages and improved key quality metrics. This led to increased yarn productivity and quality. Experiments continued with Polaris clips installed at the facility. As a result:

- Yarn breakages decreased by 40%;
- Relative breaking strength increased by 11.5%;
- Yarn unevenness according to Uster was reduced by 9%;
- USTER STATISTICS 2023 classification improved due to better yarn quality parameters.

In ring spinning process, drafting system inclination plays a vital role in twist triangle formation [4, 5]. As shown in Figure 4, the inclination angle reduces the fiber exit angle from the front rollers, influencing fiber trajectory and contributing to improved yarn structure.

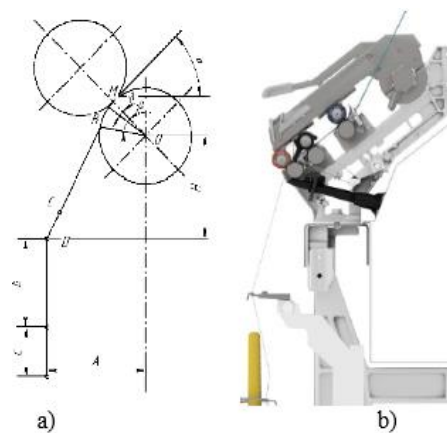


Fig. 4

The geometric parameters of the twist triangle - height, base, and slip length—affect twist uniformity and fiber consolidation. Figure 5 illustrates these parameters, emphasizing their significance in the structural quality of the yarn [6].

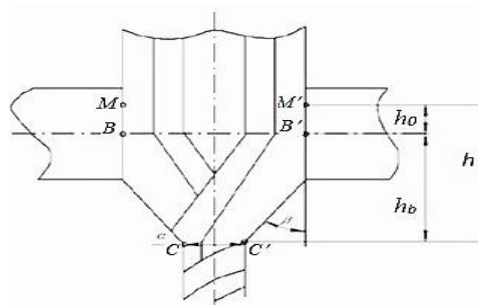


Fig. 5

The formation process of the twist triangle, affected by tension and drafting parameters, is depicted in Figure 6.

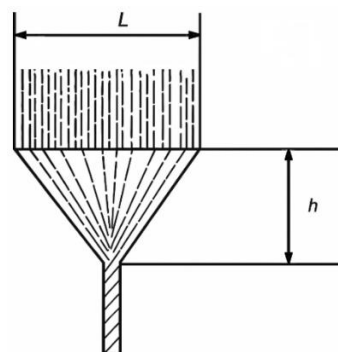


Fig. 6

To enhance spinning efficiency, specialized devices have been developed. Figure 7 shows the improved drafting and fiber delivery systems that help stabilize fiber flow and reduce turbulence [9].

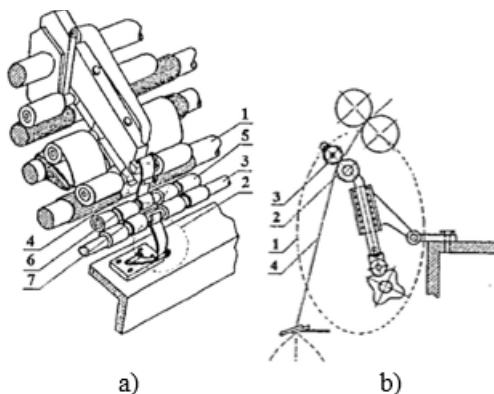


Fig. 7

Theoretical studies were conducted on fiber tension as they pass through a relief cylinder of the drafting system. A graph was constructed to show the relationship between the amplitude of vertical oscillations in the drafting system axes and the resistance of fibers to draft. According to experimental results and considering the variability in ribbon elongation and impact forces in the range of 2.3–3.0 N, the following axial vibration ranges were recorded:

- First roller: $1.7\text{--}2.4 \times 10^{-3}$ m;
- Second roller: $1.3\text{--}1.65 \times 10^{-3}$ m;
- Third roller: $0.7\text{--}1.1 \times 10^{-3}$ m (recommended to remain within this range).

The proposed improved drafting system consists of:

- Three grooved bottom rollers (1, 2, 3);
- Three pairs of load-bearing rollers (4, 5, 6) with elastic coatings;
- A spring-loaded lever (7);
- The axes of rollers 4, 5, and 6 with elastic coatings are connected by conical springs (8, 9, 10) (see Figure 8).

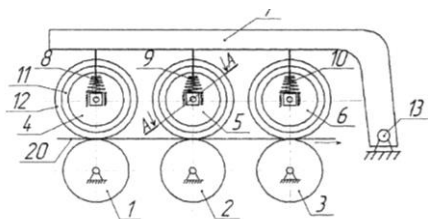


Fig. 8

The issue of increasing the strength of a yarn as a result of the effect of the number of twists on the yarn is considered through a dynamic analysis of the yarn movement during the formation of twists in the improved stretching device (see Figure 9).

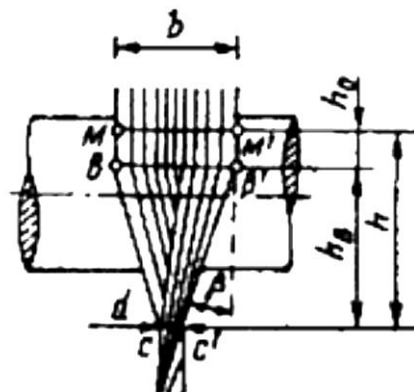


Fig. 9

Using the principle of D'Alembert, we express the problem as follows:

$$\begin{aligned} \frac{1}{\mu_0} \frac{d}{ds} \left(T \frac{dx}{ds} \right) &= 0 \\ \frac{1}{\mu_0} \frac{d}{ds} \left(T \frac{dy}{ds} \right) &= -\omega^2 y \end{aligned} \quad (1)$$

the change in the surface of the yarn during the formation of the twist.

The expression for the rotation during the formation of the yarn is defined as follows:

$$y = \frac{2 \cdot \sqrt{a \cdot (l-a)}}{\pi \cdot n} \sin \left(\frac{\pi n}{a} x \right). \quad (2)$$

This

$$\ddot{y} = -\frac{\mu_0 \omega^2}{c_1} \left(1 + \frac{1}{2} \dot{y}^2 \right) y. \quad (3)$$

Using differential equation (3), the tension force of the string is expressed as follows:

$$T = \frac{\mu_0 \omega^2 a^2}{\pi^2 n^2} \left[1 + 2 \frac{l-a}{a} \cos^2 \left(\frac{\pi n}{a} x \right) \right]. \quad (4)$$

The yarn movement and tension forces in generating the number of twists of the yarn

formed from equations (2) and (3) were analyzed graphically using the Maple program (see Figures 10-12).

From the following graphs, it is possible to correctly select the angular velocities of the yarn twists to improve the quality of the yarn, that is, to increase the tension force of the yarn at a rational value of the angular velocities when generating yarn from twists.

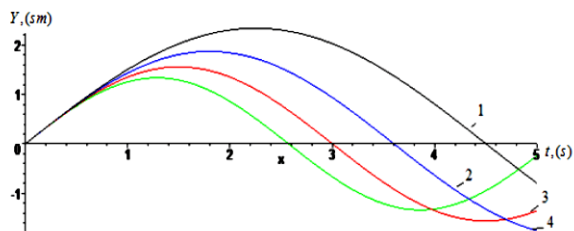


Fig. 10

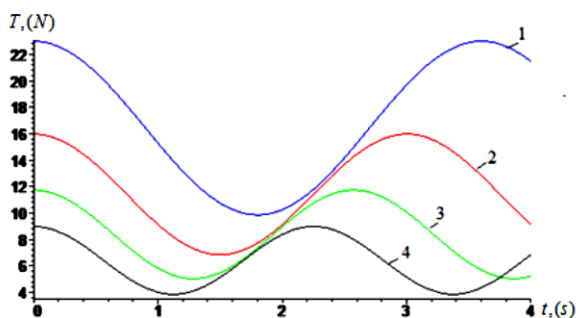


Fig. 11

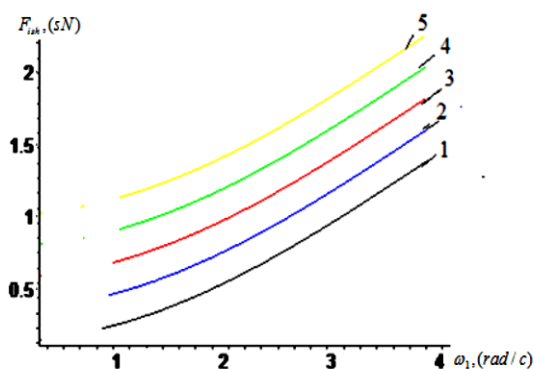


Fig. 12

The friction force is largely dependent on the stiffness of the cylinder and the yarns in the yarn formation zone, and the deformation value, i.e., density. The dependence of the friction force between the yarn formation zone and the stiffness coefficients is presented. Analysis

of the constructed graphs suggests that the friction force increases linearly from $0.19 \cdot 10$ cN to $0.52 \cdot 10$ cN when the total stiffness coefficient of the yarns in the yarn formation zone is 2.8 cN/mm and 8.0 cN/mm, and the radius of the cylinder is $r=17.5$ mm. The friction force between the yarns in the yarn formation zone increases linearly from $0.45 \cdot 10$ cN to $1.12 \cdot 10$ cN. Therefore, to increase the friction force between the twists in the yarn forming zone, it is advisable to select the friction coefficients in the range of $(7.0 \div 9.0)$ cN/mm by reducing the number of twists. In this case, it is recommended that the cylinder radius be $r=17.5$ mm. The speed of the cylinder, i.e., the work efficiency, mainly depends on the angular velocity.

We analyze the cylinder's effect on the yarn. Using the rotational motion of the second cylinder around the axis and the yarn's elasticity, we calculate the yarn's smoothness between the second cylinder and the support [10, 11]. We form a differential equation of motion under the influence of the elastic force acting on the thread when stretching it uniformly and the force of gravity at the angle of coverage:

$$J_0 \ddot{\varphi}_2 = mgl_0 - k_p l^2 \varphi_2. \quad (5)$$

Here J_0 —moment of inertia, l_0 —initial length of the yarn, l —length of the yarn after drafting, φ_2 —angle of the yarn when passing through the second cylinder, k_p —coefficient of elasticity of the yarn.

The general solution is expressed as follows:

$$\varphi = \varphi_1 + \varphi_2 = \frac{\omega_2 m R^2}{k_p l^2} \sin(zt) + \frac{g l_0 m}{k_p l^2}. \quad (6)$$

Equation (6) showed that the uniform drafting and thinning of fibers depend on the angular velocity of the second cylinder and the length of the yarn during drafting. This dependence was analyzed graphically using the Maple program (see Figure 13).

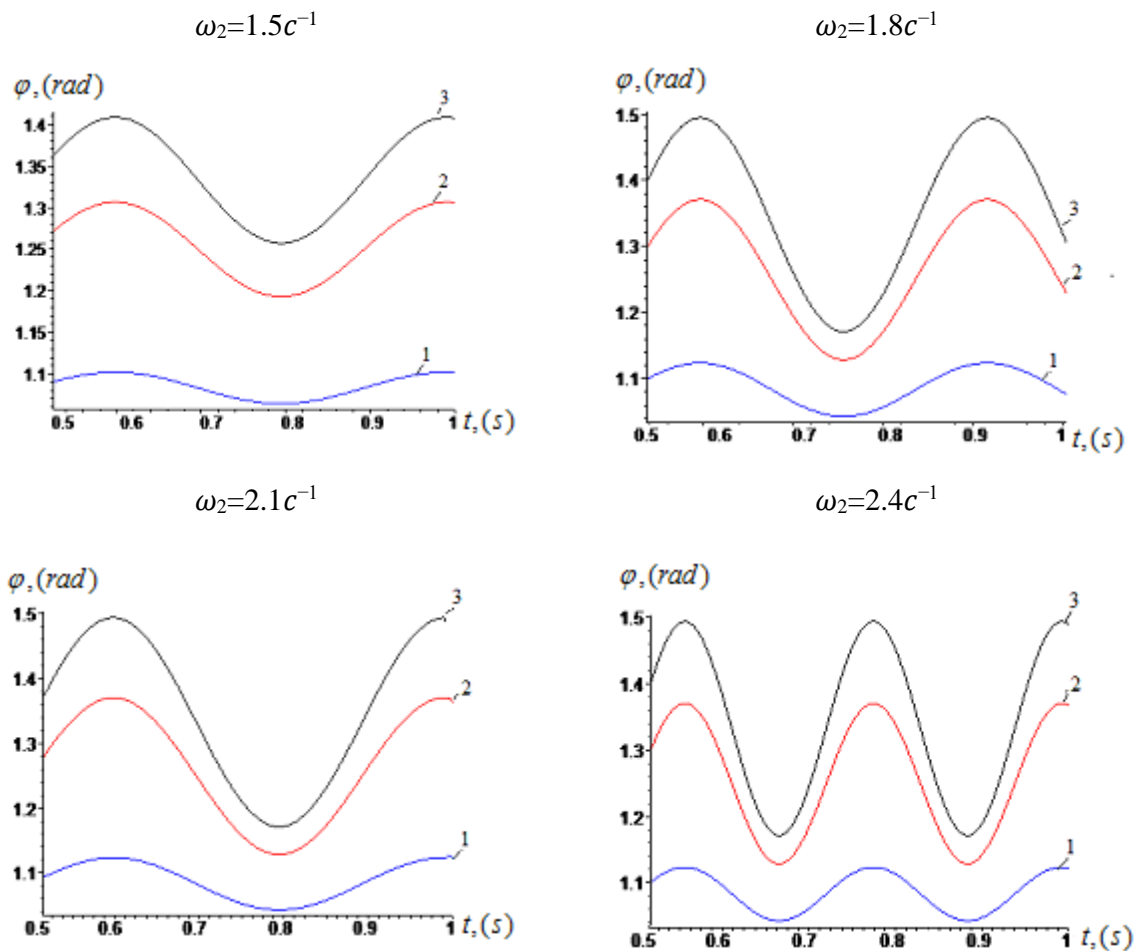


Fig. 13

We can see from the graph that the length of the thread during stretching is uniformly extended at an angular velocity of $\omega=1.5c^{-1}$ and the radius of the second cylinder is $3-R=24mm$, while reducing the unevenness of the thread's thinning.

The comprehensive research conducted on the improvement of ring-spun yarn production processes, focusing specifically on the structural geometry of the twist triangle and the drafting system, has yielded both theoretical insights and practical outcomes that hold significant implications for the textile industry. The analysis, supported by experimental validation and mathematical modeling, demonstrated how subtle yet strategic modifications to machine configurations and mechanical components can result in measurable improvements in yarn quality, consistency, and operational efficiency.

One of the most notable experimental results was the comparison of yarn breakage rates using different types of clips—standard factory-installed, Polaris-branded, and proto-

type experimental clips. Under standardized experimental conditions, utilizing a ring spinning machine model FA-516 with 516 spindles, it was observed that:

- Standard clips resulted in an average yarn breakage rate of 174 incidents per hour.
- Polaris clips reduced the rate to 103 incidents/hour, which is approximately a 40.8% reduction.
- Experimental clips achieved a rate of 135 incidents/hour, marking a 22.4% reduction compared to the control.

This substantial drop in yarn breakages translates not only to improved machine uptime and reduced downtime for repairs and thread replacement, but also increases daily and monthly yarn output. When extrapolated across a facility operating multiple FA-516 machines, this reduction could result in tens of thousands of fewer breakages per month, directly impacting economic output and profitability.

In terms of yarn quality parameters, testing under controlled conditions showed:

- Relative breaking strength increased by 11.5% using Polaris clips.
- Uster unevenness index (U%) improved by 9%, indicating more consistent yarn thickness and fewer thin/thick spots.
- These improvements led to an upgraded classification according to USTER STATISTICS 2023, reflecting better global competitiveness of the produced yarn.

These enhancements in yarn quality and performance can be attributed to better fiber alignment and reduced draft-related turbulence introduced by improved clip geometry. Particularly, Polaris clips demonstrated the ability to stabilize fiber flow through the drafting system by reducing the amplitude of oscillations in the drafting zone and maintaining consistent tension.

On a theoretical level, the study's contribution lies in modeling the dynamics of the twist triangle formation, a critical factor in ring spinning that influences twist distribution, fiber entrapment, and ultimately, yarn tenacity and appearance. Through differential equations derived from D'Alembert's principle and simulated via Maple software, it was shown that the optimal range of axial vibration for the drafting system should be limited to:

- First roller: $1.7\text{--}2.4 \times 10^{-3}$ m;
- Second roller: $1.3\text{--}1.65 \times 10^{-3}$ m;
- Third roller: $0.7\text{--}1.1 \times 10^{-3}$ m.

These values minimize the disturbance to the fiber ribbon during elongation and facilitate more uniform drafting.

Additionally, the analysis of frictional forces within the yarn formation zone highlighted that:

Friction between the yarn and cylinder increases linearly from $0.19 \cdot 10$ cN to $0.52 \cdot 10$ cN as stiffness increases from 2.8 cN/mm to 8.0 cN/mm;

Similarly, yarn-to-yarn friction in the twist zone increased from $0.45 \cdot 10$ cN to $1.12 \cdot 10$ cN under the same stiffness conditions;

Therefore, to achieve optimal fiber consolidation and minimize slippage during twist propagation, a stiffness coefficient in the range of 7.0–9.0 cN/mm is recommended, particularly when twist numbers are intentionally reduced to enhance yarn elasticity;

The angular velocity (ω) of the secondary cylinder was also explored as a function influ-

encing yarn tension and fiber orientation. Graphical analysis demonstrated that:

At $\omega = 1.5 \text{ s}^{-1}$ and a second cylinder radius of $R = 24$ mm, the drafting process yielded the most uniform fiber elongation, indicating a critical sweet spot for reducing unevenness without increasing friction or draft resistance excessively.

The redesigned drafting system incorporates grooved rollers, elastic-coated pressure rollers, and spring-lever mechanisms connected by conical springs, allowing fine-tuned response to tension changes and shock absorption. This mechanical assembly contributes directly to mitigating the stochastic disturbances caused by varying fiber lengths, friction coefficients, and raw material inconsistencies.

CONCLUSION

Critically, while the study highlights numerous strengths and improvements in yarn quality through mechanical enhancements, several limitations and areas for further exploration remain:

1. **Material Scope:** The study focused exclusively on cotton fibers. Results may vary with synthetic or blended yarns, which possess different surface frictions, tensile strengths, and elongation characteristics. Further studies should include polyester, viscose, and cotton-polyester blends.

2. **Machine Type:** All experiments were conducted on FA-516 models. The effects of modified clips and drafting systems on compact spinning machines, rotor spinning, or air-jet spinning systems remain unexplored in this work.

3. **Environmental Conditions:** Parameters such as humidity and ambient temperature were not explicitly controlled or mentioned. These can influence yarn breakages and should be standardized in future studies for greater reliability.

4. **Operator Skill Level:** While not a focus here, it is known that operator handling of spinning machines can subtly impact yarn breakage rates and tension stability. Future studies could isolate this human factor to assess the reproducibility of machine-only optimizations.

Despite these limitations, the experimental setup and modeling framework adopted in this research offer a replicable, scalable methodology for analyzing twist triangle behavior and drafting system efficiency. The integration of mechanical engineering, computational modeling, and experimental textile science is a model of interdisciplinary collaboration.

In conclusion, this study successfully validates the hypothesis that structural refinement of the drafting system—combined with optimal twist triangle geometry—can produce significant improvements in yarn quality and production stability. These improvements include: 40.8% fewer yarn breakages, 11.5% higher relative breaking strength, 9% lower yarn unevenness, and improved classification on global USTER standards.

The practical implication is a more robust and productive spinning process with lower waste, higher output, and superior yarn that meets modern textile performance criteria. As ring spinning remains a cornerstone of yarn production globally, adopting these findings into industrial practice could confer a competitive advantage to manufacturers, particularly in developing economies aiming to modernize their textile sectors.

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