1. Introduction

End breakage is the most serious problem encountered in ring spinning, the cause of which is that the peak value of yarn tension exceeds the strength of weak places in yarn. The production efficiency of ring spinning is primarily affected by the end breakage rate of yarn[1‒2]. Therefore, it is very important to measure yarn tension to improve the quality and production efficiency of ring spinning.

Ring spinning is a yarn formation process characterized by the drafting, twisting, spinning and winding of fiber strands[3]. The strands of the drafted rovings pass through the thread guide and subsequently through the traveler and are wound around the bobbin under the action of the high-speed rotating spindle. Four types of yarn tension are associated with different stages of ring spinning, i.e., the upstream tension $T_I$ in the spinning triangle zone, the top-ballooning tension $T_{q1}$ and bottom-ballooning tension $T_{q2}$ in the yarn-ballooning zone, and the winding tension $T_w$ in the winding zone. Therefore, the real-time dynamics of yarn tension offer insight into the origin of breakage and abnormal yarn tension throughout the ring spinning process.

In general, detection of yarn tension includes a contact measurement method and a noncontact measurement method[4‒6]. In the contact measurement method[7‒8], the running length of yarn interacts with an external device that measures the impact of yarn on the device, e.g., torque, mechanical power, force, or work. However, the interaction between the yarn and device results in additional friction forces that affect the accuracy of the measurement. The noncontact measurement method includes two main approaches, the optoelectronic type[9‒10] and electromagnetic type[11‒12]. For both types, a detector monitors the movement of the traveler, which can be related to the dynamics of yarn tension after processing electronic signals with an A/D converter. However, this method fails to detect breakage for multichannel drafted spun yarn[13‒15] as the sensor continues to detect signals after the breakage of the roving from one channel. In addition, only a few studies have investigated the variation features of yarn tension in ring spinning[16‒17], especially with respect to the collective behaviors of yarn tension associated with different stages of ring
spinning, which supplies valuable information on the performance of the ring spinning machine. Therefore, we believe an urgent need exists to develop both analytical and experimental tools to predict the yarn tension values and to analyze their variation characteristics.

In this work, we use a self-developed device to measure yarn tension. Force sensors are attached to the guide plate to measure the pressures applied by yarn. Displacement sensors are attached to the guide plate and ring rail to measure their displacements. Coupled physical-mathematical equations that describe the variations of yarn tension in the ring-spinning process are solved to obtain the real-time dynamics of yarn tension.

2. Materials and Methods

In this work, force and displacement sensors are attached to the guide plate and ring rail, as shown in Fig. 1. The force sensors are attached to the guide plate to measure the vertical and horizontal tensions of yarn. A displacement sensor is attached to the guide plate to measure the vertical displacement, \( x \), of the guide plate, and the other displacement sensor is attached to the ring rail to measure the vertical displacement, \( h \).

The actual sensor element is the strain gauge, which consists of an insulation layer with a measuring grid attached [18–19]. Fig. 2 shows the structure of the force sensor with four strain gauges attached to it. Fig. 3 shows the structure of the force sensor, and Fig. 4 shows the structure of the full-bridge and equi-arm bridge circuit. As illustrated in Fig. 5 (a), when yarn exerts pressure on the thread guide, it leads to changes in the stress and strain of the force sensor, which result in changes in the electrical resistance of the force sensor. The variations of resistance are processed by the full-bridge and equi-arm bridge circuit.
circuit and are output as electrical signals. A signal amplifier magnifies the output signals before they are processed by the programmable logic control (PLC) system via A/D conversion and are ultimately converted into digital numbers that represent the magnitudes of the types of yarn tension. The photographs of force sensors, displacement sensor, signal magnifier, PLC controller and touch screen are demonstrated in Fig. 5 (b)‒(f).

The displacement sensor converts the displacements of the guide plate and ring-rail into electrical signals. The PLC processes the output signals for A/D analog-digital conversion.

Fig. 6 shows a diagram illustrating the different yarn tensions at the thread guide. The center of the thread guide is denoted as $O$ and the $X$, $Y$- and $Z$-axes pass through point $O$. The $X$-axis is perpendicular to the plane that holds the guide plate, the $Y$-axis is parallel to the plane that holds the guide plate, and the $Z$-axis is vertical to the $X$-$O$-$Y$ plane. Therefore, a three-dimensional coordinate system is built with the center of the thread guide as the origin. Similarly, an $X'$-$Y'$-$Z'$ coordinate system is built with the center of the ring rail as the origin. Both the upstream and downstream yarn tensions cause a change in voltage that is proportional to the yarn tension. The values of $F_x$ and $F_z$ can be measured through the force sensors. In addition, the vertical displacement of the guide plate can be measured through the displacement sensor.

Yarn formation in ring spinning is a nonlinear and inhomogeneous process[3]. In general, yarn
tension is related to the traveler mass, ring-rail movement, spindle speed, ring diameter, and coefficient of friction between the ring and traveler. Variations of these parameters cause a change in balloon shape. Therefore, the four spinning tensions are associated with geometric parameters, which are the guide angle $\gamma$, the top ballooning angle $\beta$ and the wrapping angle $\delta$ of yarn around the thread guide.

The guide angle $\gamma$ is the angle between the attenuated roving and the $XY$-plane, which is a function of the displacement of the guide plate $[3]$:

$$\gamma = \varphi(x) \quad (2)$$

The top ballooning angle $\beta$ is the angle between the tangent line and the $Z$-axis, which is a function of, $F_s, F_z,$ and guide angle $\gamma$ $[3]$:

$$\beta = \Phi(F_s, F_z, \varphi(x)) \quad (3)$$

As shown in Figure S, the wrapping angle $\delta$, which corresponds to the portion of yarn wrapped around the thread guide, can be written as:

$$\delta = 90 - \gamma + \beta \quad (4)$$

Therefore, the wrapping angle is a function of the guide angle $\gamma$ and top ballooning angle $\beta$ $[3]$:

$$\delta = \Xi(\varphi(x), \Phi(F_s, F_z, \varphi(x))) \quad (5)$$

By combining Eqns. (2)-(4), the four spinning tensions can be expressed as follows:

$$T_f = F_0 \left[ \varphi(x), \Phi(F_s, F_z, \varphi(x)), \Xi(\varphi(x), \Phi(F_s, F_z, \varphi(x))) \right] \quad (6)$$

$$T_\psi = F_1 \left[ \varphi(x), \Phi(F_s, F_z, \varphi(x)), \Xi(\varphi(x), \Phi(F_s, F_z, \varphi(x))) \right] \quad (7)$$

$$T_w = F_2 \left[ \varphi(x), \Phi(F_s, F_z, \varphi(x)), \Xi(\varphi(x), \Phi(F_s, F_z, \varphi(x))) \right] \quad (8)$$

$$T_u = F_3 \left[ \varphi(x), \Phi(F_s, F_z, \varphi(x)), \Xi(\varphi(x), \Phi(F_s, F_z, \varphi(x))) \right] \quad (9)$$

From Eqns. (6)-(9), it can be observed that the yarn spinning tensions are functions of, $F_s, F_z,$ and the displacement of the guide plate. Therefore, we can obtain the four yarn spinning tensions after we measure, $F_s, F_z,$ and the displacement of the guide plate using the self-developed device. The detailed derivation and the mathematical expressions for the four yarn spinning tensions and geometric parameters are supplied in the supplemental materials.

For our experiments, the yarn is made of cotton, the linear density of the yarn is set to 19.4 tex, and the yarn twist is set to 77.1 twists/0.1 m. The dynamic friction coefficient is 0.25 $[20-21]$; the minimum spindle speed is set to 10000 r/min, and the maximum spindle speed is set to 11000 r/min.

### 3. Results and discussion

It can be observed from Fig. 7 that when the...
spindle rotation speed is 11000 r/min, the time spent in one up-and-down reciprocating cycle is shorter than that at a spindle speed of 10000 r/min. In addition, a longer time is spent in the rising process than in the falling process. In the rising process, yarn is wound around the bobbin, and thus, the speed is slower. The falling process reinforces the wound package on the bobbin, and thus, the falling process proceeds more quickly. By recording the displacements of the guide plate and ring rail, it is found that the balloon height is greater at the bottom of the bobbin and smaller at the top of the bobbin, indicating that our self-developed device behaves correctly.

The measured, $F_x$, and, $F_z$, in one up-and-down reciprocating cycle are shown in Fig. 8. It can be observed from Fig. 8 that the variations of the horizontal and vertical tensions are smaller when the ring rail is at the lower position and are larger when the ring rail is at the upper position. Ideally, yarn tension should smoothly vary, but in actual production, it is affected by the vibrations of the spinning machine due to the rotations of the spindle, traveler and drafting rollers[16], thereby resulting in certain fluctuations in yarn tension.

The variations of the geometric parameters can be obtained by substituting the measured tensions and displacements into Eqns. (5)-(7). As can be observed from Fig. 9, the geometric parameters show similar periodical changes. When the ring rail is at the lower position, the guide angle, the top ballooning angle and the wrapping angle are larger than those when the ring rail is at the higher position. In particular, the top ballooning angle shows certain fluctuations due to the uneven distribution of fibers in yarn ballooning, which affects the balloon shape in the spinning process[22–23], resulting in fluctuation of the top ballooning angle. The wrapping angle also shows certain fluctuations because it is related to the guide angle and the top ballooning angle, according to Eqn. (4).

Fig. 10 shows that when the ring rail is at the lower position, the balloon height is greater and the balloon radius is larger than when the ring rail is at

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**Fig. 8** Measured a) horizontal tension and b) vertical tension under different spindle speeds in one up-and-down reciprocating cycle.

**Fig. 9** Variations of the a) guide angle, b) top ballooning angle and c) wrapping angle under different spindle speeds in one up-and-down reciprocating cycle.
the upper position, but the winding radius is large at this moment, which makes the yarn tensions small. When the ring rail is at the upper position, the balloon height is lower and the balloon radius is smaller than when the ring rail is at the lower position, but the winding radius is notably small at this moment, and thus, the yarn tensions are large. Moreover, the yarn tensions at a spindle speed of 11000 r/min are generally greater than those at a spindle speed of 10000 r/min, with certain abnormal values due to the uneven fiber distributions in yarn ballooning. Therefore, the greater the spindle speed, the greater the spinning tension, which is consistent with the results of Rengasamy et al.[1]. The maximum ratio of tension at 11000 r/min to that at 10000 r/min is approximately 9.5%. Furthermore, Fig. 10 shows that the relative order of the magnitudes of the four spinning tensions is \( T_f < T_2 < T_1 < T_w \), which is consistent with previous studies[3, 16, 24–25].

6. Conclusions

In this work, we developed a device to measure yarn tension in a ring spinning frame. With sensors attached to a ring frame, we measured the real-time dynamics of yarn tension when yarn passed over the thread guide. Moreover, we analyzed the yarn tension in ring spinning in which several factors contribute to yarn tension. In particular, the spinning tensions are primarily affected by the wrapping angle, the guide angle and the top ballooning angle in ring spinning. By solving coupled physical-mathematical equations, we obtained the wrapping angle, the guide angle and the top ballooning angle based on the measured values of the horizontal and vertical tensions of yarn as well as the displacement of the guide plate using a self-developed device. Finally, we analyzed the variation features of the yarn tensions in ring spinning and found that both the geometric parameters and yarn tensions showed periodical changes. In particular, the yarn tensions are smaller when the ring rail is at the lower position, whereas they become larger when the ring rail is at the upper position. In contrast, the variations of the geometric parameters show the opposite trends with respect to the movement of the ring rail.

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Fig. 10 Variations of the a) upstream tension, b) top ballooning tension, c) bottom ballooning tension and d) winding tension under different spindle speeds in one up-and-down reciprocating cycle.
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Supplemental Detection and Analysis of Real-time Dynamics of Yarn Tensions in a Ring Spinning Frame

According to Figure S1:

\[ F_x = T_q \sin \beta \sin \alpha \]
\[ F_y = T_q \sin \beta \cos \alpha \]
\[ F_z = T_q \cos \beta - T_f \sin \gamma \]

where \( \gamma \) represents the guide angle (°) between the attenuated roving and the \( XY \)-plane, \( \beta \) represents the top ballooning angle (°) between the tangent line and the \( Z \)-axis, and \( \alpha \) is the angle (°) between the \( Y' \)-axis and the tangent line to an arbitrary point in the \( X'Y' \) plane (°).

According to Euler’s formula[1]:

\[ T_f = T_o e^{-\mu \delta} \]

After substituting Eqn. (4) into Eqn. (3), the upstream tension \( T_f \) can be written as:

\[ T_f = \frac{F_z}{e^\mu \cos \beta - \sin \gamma} \]

where \( \mu \) refers to the dynamic friction coefficient between the yarn and the thread guide. Barr and Catling[2] found that for cotton yarn \( \mu \) is chosen to be 0.25, and \( \delta \) refers to the wrap angle of the yarn around the thread guide, as shown in Fig. S2.

\[ \text{Fig. S2} \quad \text{Schematic diagram illustrating the movement of roving across the thread guide.} \]

By substituting Eqn. (4) into Eqn. (3), we obtain the expression of the top ballooning tension:

\[ T_{\beta i} = \frac{F_z}{e^\mu \cos \beta - \sin \gamma} \]

The relationship between the top and bottom ballooning tensions is written as[3]:

\[ T_{\beta i} = T_{\beta o} + \frac{1}{2} m R_g \omega^2 \]

where \( R_g \) refers to the radius of the ring rail, \( m \) refers to the linear density of yarn and \( \omega \) refers to the rotation speed of ballooning, which is approximately equal to the rotation speed of the spindle.

By substituting Eqn. (6) into Eqn. (7), we obtain the expression of bottom ballooning tension:

\[ T_{\beta o} = \frac{F_z}{e^\mu \cos \beta - \sin \gamma} \]

The bottom ballooning tension is related to the winding tension \( T_w \) by the following equation:

\[ T_w = K T_{\beta o} \]

After substituting Eqn. (8) into Eqn. (9), the winding tension \( T_w \) is written as:

\[ T_w = K \left( \frac{F_z}{e^\mu \cos \beta - \sin \gamma} - \frac{1}{2} m R_g \omega^2 \right) \]

where \( K \) refers to the ratio between the winding tension and the bottom ballooning tension, which changes with the shape of the cross-section of the traveler. In general, the shape of the cross-section is a rectangle, and \( K \) is determined to be 1.7 according to the reference[3].
Forces, $F_x$ and $F_z$, can be measured by the sensor. Therefore, the geometric parameters, including the guide angle $\gamma$, angle $\beta$ and wrapping angle $\delta$ should be supplied to solve for $T_f$, $T_{q1}$, $T_{q2}$, and $T_w$.

The variations of the geometric parameters are caused by the up and down movements of the ring rail and thread guide. Therefore, an analytical model is built to describe the relationship of the geometric parameters with respect to the positions of the thread guide and ring rail. During yarn spinning, the traveler drives the yarn to rotate around the spindle. It is assumed that only the direction of the guide angle varies with the yarn rotation, as shown in Fig. S3.

According to the geometric relationship shown in Fig. S3, the guide angle is written as:

$$\gamma = \tan^{-1} \left( \frac{h - x}{\alpha - R_q \sin \gamma} \right)$$  \hspace{1cm} (11)

where $a$ refers to the horizontal distance from the center of the thread guide to the center of the bottom roller, $h$ refers to the vertical distance from the guide plate to the center of the bottom roller, $R_q$ refers to the radius of the bottom roller, $x$ refers to the vertical displacement of guide plate, and $b$ refers to the displacement of the ring rail.

Based on the algebraic relationship (i.e., Eqns. (1) and (3)) between $F_x$ and $F_z$, and assuming that $\alpha$ is 90 degree, the top ballooning angle can be derived as:

$$\beta = \varphi - \sin^{-1} \left( \frac{F_x \sin \gamma + F_z \cos \gamma}{\sqrt{F_x^2 - F_z^2}} \right)$$ \hspace{1cm} (12)

Based on the forces, $F_x$ and $F_z$, and the displacement, $x$, we can calculate the guide angle $\gamma$, top ballooning angle $\beta$ and wrapping angle $\delta$, using Eqns. (11)-(14) and subsequently solve for the upstream tension $T_f$, top ballooning tension $T_{q1}$, bottom ballooning tension $T_{q2}$ and winding tension $T_w$, using Eqns. (5)-(10), which offer insight into the mechanics of blended yarn.

$$\tan \varphi = \frac{F_x}{F_z}$$ \hspace{1cm} (13)

When the roving rotates along the spindle, the wrapping angle reaches the minimum value as the traveler moves to the farthest location of the ring, whereas it reaches the maximum value as the traveler moves to the opposite side of the ring, as shown in Fig. S3.

According to the geometric relationship, the wrapping angle is expressed as:

$$\delta = 90 - \gamma + \beta$$ \hspace{1cm} (14)

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