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Characterization of the Twist Distribution Function and Twist Unevenness of Self-twist Yarns

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Abstract
In in-phase self-twist yarn there exists an obviously weak twist area between the twisted and no twisted zones. Therefore, during the self-twist spinning process, different distances from the two strands to the convergence point is adopted to produce a certain phase difference to improve the yarn strength. There are two methods used for calculating the twist distribution function of self-twist yarn: 1. using the difference in distance c, and 2. using the twist distribution function of strands A and B, respectively. Then the average twist over a half cycle length is calculated by the twist distribution functions from the two methods mentioned above. Comparing the calculation value from the two methods with actual test twists for the half cycle length, the result shows that the calculation value from method 2 is closer to the values measured, namely the twist distribution function derived from that of strands A and B, respectively. The twist unevenness of self-twist yarn is calculated by the twist distribution function from method 2. The twist unevenness of yarn 1 is the highest. That of yarns 2 and 3 decreases in turn. From the test data of 49×2 tex and 113×2 tex self-twist yarns, in-phase self-twist yarn 1, with maximum twist unevenness, has the minimum tenacity and maximum unevenness of tenacity, and in the same way phased self-twist yarn 3, with the minimum twist unevenness, has the maximum tenacity and minimum unevenness of tenacity.

Key words: *self-twist, twist distribution function, twist unevenness, average twist, breaking tenacity.*

Introduction

In-phase self-twist yarn obviously has a weak twist area between the twisted and no twisted zones [1]. Therefore, during the self-twist spinning process, different distances from the two strands to the convergence point is adopted to produce a certain phase difference to improve the yarn strength. A certain phase difference can make the twistless point misplace a certain distance so as to form a two-ply structure self-twist yarn in which there is twist on one strand and simultaneously no twist on the other. Thereby the length of the weak twist zone on the self-twist yarn is reduced to improve the yarn tensile properties [2 - 4].

Henshaw [5] investigated the factors that affect the distribution of strand twist and ply twist for in-phase self-twist yarns, and a conclusion was drawn that the strand tension and strand twist were the main factors influencing the twist distribution in a self-twist yarn. Allen [6] presented the relation between the pressure of self-twist rollers and the twists of self-twist yarns and the effect of the surface coating material of self-twist rollers on the twists of self-twist yarns. Henshaw [7] built up a mathematical model of the yarn structure and relationships between the twist of self-twist yarn and that of each strand. In his study, Ellis [8] proposed a better understanding of self-twist structures. However, little research has been carried out on the study of the correction between the twist distribution function and calculation of the twist irregularity for self-twist yarns. This study proposed two calculation methods to compare the correction of the twist distribution functions and discussed the effect of twist irregularity on the variation in the breaking strength of self-twist yarns.

Calculation of twist distribution functions using two methods

The phase difference is realised by the different convergence modes shown in ***Figure 1***. Yarn 1 is in-phase self-twist yarn, and yarns 2 and 3 are self-twist yarns with a certain phase difference, respectively [9, 10]. Let c mean the difference in distance from the self-twist roll-

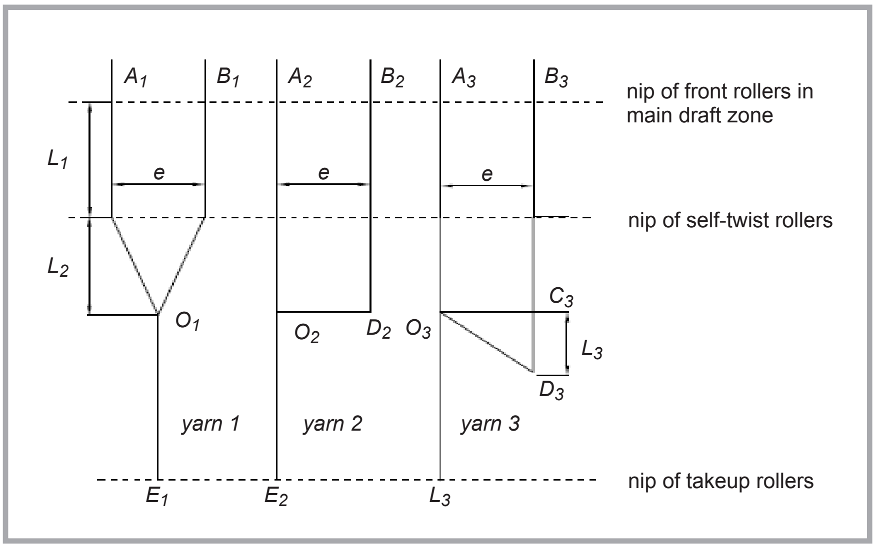

Figure 1. *Phase difference in different convergence modes; e - distance of two strands, L_1 - distance from the nip of front rollers 1 to that of self-twist rollers 2, L_2 - distance from the nip of self-twist rollers 2 to the convergence point O, L_3 - vertical distance between the convergence hook C_3 and guide D_3 (yarn 3), O_1 - convergence point of strands A_1 and B_1, O_2 - convergence point of strands A_2 and B_2, O_3 - convergence point of strands A_3 and B_3.*

ers to the convergence guide between the two strands, then $c = 0$ for yarn 1 (which means in yarn 1 the strands A and strand B have the same distance from the self-twist rollers to the convergence guide); $c = O_2D_2 = e = 19$ mm for yarn 2 (which means in yarn 2, strands A and B have a 19 mm difference in distance from the self-twist rollers to the convergence guide); e is the feeding distance of the two strands, $c = C_3D_3 + O_3D_3 = 43$ mm for yarn 3 (which means in yarn 2, strands A and B have a 43 mm difference in distance from the self-twist rollers to yheconvergence guide).

The twist distribution function $T(Z)$ [4] for yarn section L_2 from the nip of the self-twist rollers to the convergence guide is ***Equation 1***, where, X - cycle length (length of yarn passed during a complete cycle of oscillation of the rollers), D - reciprocating stroke of self-twist rollers, Z - delivery length, p - perimeter of strand in mm.

$$\begin{cases} T(Z) = \dfrac{2\pi^2 \mathrm{DL_1}}{p\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2L_2^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta\right) \\ \beta = \arctan\dfrac{\mathrm{X^2-4\pi^2L_1L_2}}{2\pi X(\mathrm{L_1+L_2})} \end{cases} \tag{1}$$

$$\begin{cases} T_{\mathrm{st1}}(Z) = \dfrac{1}{2\sqrt{2}}[\mathrm{T(Z)+T(Z+c)}] & \mathrm{T(Z)\cdot T(Z+c)} \geq 0 \\ 0 & \mathrm{T(Z)\cdot T(Z+c)} < 0 \end{cases} \tag{2}$$

$$\begin{cases} T_{\mathrm{st1}}(Z) = \dfrac{1}{2\sqrt{2}}[\dfrac{2\pi^2 \mathrm{dL_1}}{p\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2L_2^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta\right)+ \\ +\dfrac{2\pi^2 \mathrm{dL_1}}{p\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2L_2^2}}\sin\left(\dfrac{2\pi\mathrm{(Z+c)}}{X}+\beta\right)] \\ \beta = \arctan\dfrac{\mathrm{X^2-4\pi^2L_1L_2}}{2\pi X(\mathrm{L_1+L_2})} \end{cases} \tag{3}$$

$$\begin{cases} T_{\mathrm{st2}}(Z) = \dfrac{1}{2\sqrt{2}}[\mathrm{T_A(Z)+T_B(Z)}] & \mathrm{T_A(Z)\cdot T_B(Z)} \geq 0 \\ 0 & \mathrm{T_A(Z)\cdot T_B(Z)} < 0 \end{cases} \tag{4}$$

$$\begin{cases} T_{\mathrm{st21}}(\mathrm{Z}) = \dfrac{1}{\sqrt{2}}\left[\dfrac{2\pi^2\mathrm{DL_1}}{\mathrm{P}\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+\pi^2\mathrm{e}^2+4\pi^2\mathrm{L}_2^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta_1\right)\right] \\ \beta_1 = \arctan\dfrac{\mathrm{X}^2-4\pi^2L_1\sqrt{\mathrm{e}^2+4\mathrm{L}_2^2}}{2\pi X(L_1+\sqrt{\mathrm{e}^2+4\mathrm{L}_2^2})} \end{cases} \tag{5}$$

$$\begin{cases} T_{\mathrm{st22}}(\mathrm{Z}) = \dfrac{1}{2\sqrt{2}}\left[\dfrac{2\pi^2\mathrm{DL_1}}{\mathrm{P}\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2\mathrm{L}_2^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta_{\mathrm{A2}}\right)+\right. \\ \qquad\left.+\dfrac{2\pi^2\mathrm{DL_1}}{\mathrm{P}\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2(\mathrm{L_2+e})^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta_{\mathrm{B2}}\right)\right] \\ \beta_{\mathrm{A2}} = \arctan\dfrac{\mathrm{X^2-4\pi^2L_1L_2}}{2\pi X(\mathrm{L_1+L_2})}, \beta_{\mathrm{B2}} = \arctan\dfrac{\mathrm{X^2-4\pi^2L_1(L_2+e)}}{2\pi X(\mathrm{L_1+L_2+e})} \end{cases} \tag{6}$$

$$\begin{cases} T_{\mathrm{st23}}(\mathrm{Z}) = \dfrac{1}{2\sqrt{2}}\left[\dfrac{2\pi^2\mathrm{DL_1}}{\mathrm{P}\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2\mathrm{L}_2^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta_{\mathrm{A3}}\right)+\right. \\ \qquad\left.+\dfrac{2\pi^2\mathrm{DL_1}}{\mathrm{P}\sqrt{X^2+4\pi^2L_1^2}\sqrt{X^2+4\pi^2(L_2+L_3+\sqrt{\mathrm{e}^2+L_3^2})^2}}\sin\left(\dfrac{2\pi Z}{X}+\beta_{\mathrm{B3}}\right)\right] \\ \beta_{\mathrm{A3}} = \arctan\dfrac{\mathrm{X^2-4\pi^2L_1L_2}}{2\pi X(\mathrm{L_1+L_2})}, \beta_{\mathrm{B3}} = \arctan\dfrac{\mathrm{X}^2-4\pi^2L_1(L_2+L_3+\sqrt{\mathrm{e}^2+L_3^2})}{2\pi X(L_1+L_2+L_3+\sqrt{\mathrm{e}^2+L_3^2})} \end{cases} \tag{7}$$

Equations 1, 2, 3, 4, 5, 6, and 7.

The twist distribution function of self-twist yarn can be calculated by two methods: 1. using the difference in distance c, and 2. using the twist distribution function of strands A and strand B, respectively. The relation coefficient between the twists of self-twist yarn and those in the strand is $2\sqrt{2}$, proposed by Ellis [7].

Twist distribution function $T_{st1}(Z)$ calculated by method 1

In ***Equation 2***, when $T(Z)\cdot T(Z + c) < 0$ it means the directions of twist in the two strands are opposite, that self-twist has not happened and the twists in the self-twist yarn is zero; when $T(Z)\cdot T(Z + c) \geq 0$, it means the directions of twist in the two strands are same, and that self-twist has happened.

By substituting ***Equation 1*** into ***Equation 2***, the twist distribution function for yarn section L_2 is shown as ***Equation 3***.

Twist distribution function $T_{st2i}(Z)$ (i = 1, 2, 3) calculated by method 2

In ***Equation 4***, when $T_A(Z)\cdot T_B(Z) < 0$ it means the directions of twist in strands A and B are opposite, that self-twist has not happened, and the twists in the self-twist yarn are zero; when $T_A(Z)\cdot T_B(Z) \geq 0$, it means the directions of twist in strands A and B are the same, and that self-twist has happened.

The expressions of twist distribution function calculated by method 2 in different yarns are shown as follows:

When c = 0 mm, strands A_1 and B_1 have equal distance $\sqrt{\frac{\mathrm{e}^2}{4}+\mathrm{L}_2^2}$ from the self-twist rollers to the convergence guide O_1; the expression of twist distribution function $T_{st21}(Z)$ of yarn 1 is ***Equation 5***.

When c = 19 mm, the distance from strand A_2 to the convergence guide O_2 is L_2; the distance from strand B_2 to the convergence guide O_2 is $(L_2 + e)$, and the expression of the twist distribution function $T_{st22}(Z)$ of yarn 2 is ***Equation 6***.

When c = 43 mm, the distance from strand A_3 to the convergence guide O_3 is L_2, that from strand B_3 to the convergence guide O_3 $L_2+L_3+\sqrt{\mathrm{e}^2+L_3^2}$, and the expression of the twist distribution function $T_{st23}(Z)$ of yarn 3 is ***Equation 7***.

Graphs of twist distribution functions by the two methods

In self-twist spinning, the parameters employed aare D = 76 mm, L_1 = 45 mm, L_2 = 15 mm, e = 19 mm, L_3 = 17 mm and X = 210 mm. The corresponding c value of the three convergence modes is 0, 19 and 43 mm, respectively.

The twist distribution function calculated by method 1 with the parameters above is:

$$T_{st1}(Z)=\frac{1}{2\sqrt{2}}\left[9.4\sin\left(\frac{\pi Z}{105}+\frac{12.43\pi}{180}\right)+\right.$$
$$\left.+9.4\sin\left(\frac{\pi(Z+c)}{105}+\frac{12.43\pi}{180}\right)\right]$$

The twist distribution function calculated by method 1 is drawn in ***Figure 2***.

The twist distribution function by method 1 in the actual spinning condition is:

c = 0

$$T_{st21}(Z)=\frac{1}{\sqrt{2}}\left[9.1\sin\left(\frac{\pi Z}{105}+\frac{8.63\pi}{180}\right)\right]$$

c = 19

$$T_{st22}(Z)=\frac{1}{2\sqrt{2}}\left[9.4\sin\left(\frac{\pi Z}{105}+\frac{12.43\pi}{180}\right)+\right.$$
$$\left.+7.2\sin\left(\frac{\pi Z}{105}-\frac{8.89\pi}{180}\right)\right]$$

c = 43

$$T_{st23}(Z)=\frac{1}{2\sqrt{2}}\left[9.4\sin\left(\frac{\pi Z}{105}+\frac{12.43\pi}{180}\right)+\right.$$
$$\left.+5.2\sin\left(\frac{\pi Z}{105}-\frac{23.23\pi}{180}\right)\right]$$

The twist distribution function calculated by method 2 is drawn in ***Figure 3***.

Experiment

Acrylic fibres with a fineness of 3.3 dtex and length of 102 mm and wool fibres with a diameter of 22 μm and length of 78 mm were spun to produce self-twist yarns on an S300 self-twist spinning system. The average counts were 50 tex wool/acrylic blended self-twist yarn for average twists and 49×2 tex & 113×2 tex wool/acrylic blended self-twist yarn for different convergence modes. The yarns were conditioned at 65% RH and 25 °C for 24 hours before twist and tensile testing. Yarn twists were determined by a YG155 twist tester (Changzhou Second Textile Instrument Co., Ltd., China). The self-twist per half cycle length was determined by untwisting the yarn at a 105 centimeter length (half cycle length) until the fibres became parallel, and twenty data were taken on average. Tensile properties of the self-twist yarn were evaluated by a YG061 tensile tester (Shanxi Changling Textile Machinery & Electrical Technology Co., Ltd., China) and fifty data were taken on average.

Calculation of the average twists

The average twists of 50 tex self-twist yarn were calculated by methods 1 and 2.

$$\overline{T_{st}}(Z)=\frac{1}{\frac{X}{2}-0}\int_0^{\frac{X}{2}}T_{st}(Z)dZ$$

where, $T_{st}(Z)$ is the twist distribution function of the self-twist yarn.

Comparison of the value of average twists calculated with the test value is shown in ***Table 1***.

As is shown in ***Table 1***, the maximum error percentage reache 52.7% from the calculated value and test value of average twists by method 1, while the max. error percentage can achieve only 9.2% by method 2. Therefore the average twists calculated by method 2, whose twist distribution function was expressed by the twist distribution functions of the two strands, respectively, are much closer to the actual production.

Table 1. *Calculated value and test value of average twists.*

	yarn 1	yarn 2	yarn 3
Method 1	24.2	21.0	13.1
Method 2	23.7	21.4	18.3
Tested data	22.4	20.5	20.0

Calculation of the twist unevenness

The twist unevenness of yarn 1 was calculated according to ***Equation 5***.

The average twists of in-phase self-twist yarn 1 is shown in ***Equation 8*** (see page 48).

The variance of twists is shown in ***Equation 9*** (see page 48).

$$\text{Twist unevenness } CV\% = \frac{\sqrt{D(T_{st11}(Z))}}{E(T_{st11}(Z))}$$

Similarly the theoretical twist unevenness can be calculated according to ***Equations 6 and 7***. Substituting the practical processing parameters in the twist unevenness formula, the results are shown in ***Table 2*** (see page 48).

It is evident from ***Table 2*** that the average twists of yarn 1 is 41.46 per half cycle length, and is 37.49 higher than that of yarn 2 and 32.09 higher than that of yarn 3. Although the in-phase self-twist

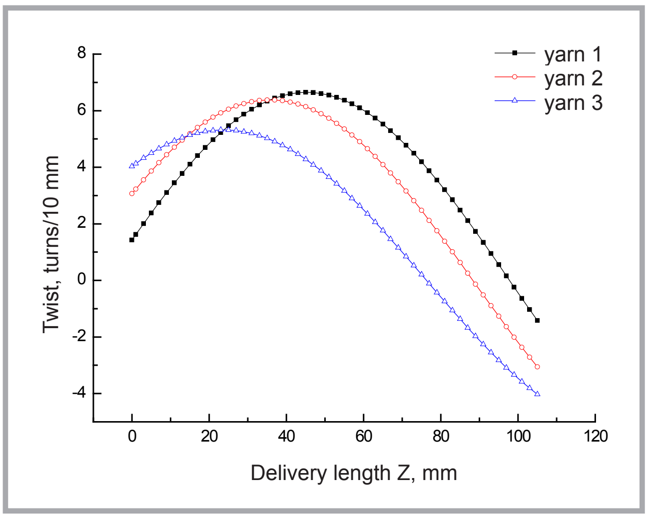

Figure 2. *Twist distribution function graph by method 1.*

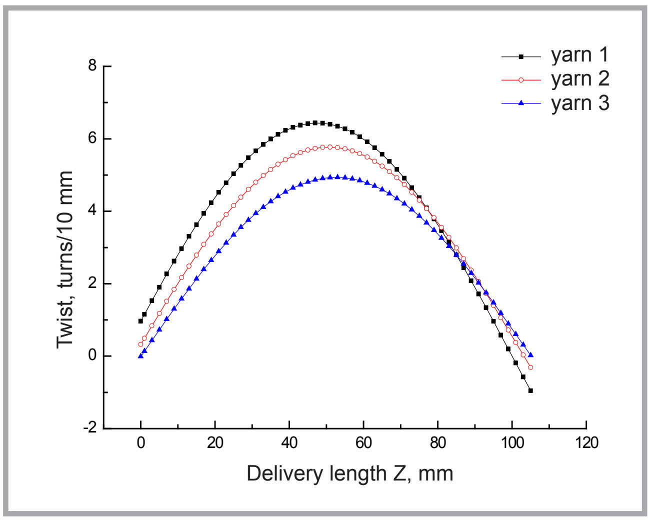

Figure 3. *Twist distribution function graph by method 2*

$$\overline{T}_{st11}(Z) = E(T_{st11}(Z)) = \frac{1}{\frac{X}{2}-0}\int_0^{\frac{X}{2}} \frac{1}{\sqrt{2}}\left[\frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}}\sin\left(\frac{2\pi Z}{X}+\beta_1\right)\right]dZ = \tag{8}$$

$$= \frac{4\pi DL_1}{\sqrt{2}P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}}\cos\beta_1$$

$$D(T_{st11}(Z)) = \frac{1}{N}\sum_{i=1}^{N}[T_{st11}(Z) - E(T(Z))]^2 =$$

$$= \frac{1}{N}\sum_{i=1}^{N}[\frac{1}{\sqrt{2}}\left[\frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}}\sin\left(\frac{2\pi Z}{X}+\beta_1\right)\right] + \tag{9}$$

$$- \frac{4\pi DL_1}{\sqrt{2}P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}}\cos\beta_1]^2$$

Equations 8, 9.

Table 2. *Twist unevenness and practical breaking properties.*

Items		yarn 1	yarn 2	yarn 3
Average twists, turns/half cycle length		41.46	37.49	32.09
Variance of twists		246.86	186.13	135.40
Twist unevenness CV%		38.82	37.29	37.11
49×2 tex	Tenacity(cN/tex)	3.5	5.5	6.1
	Tenacity CV%	26.0	24.4	24.3
113×2 tex	Tenacity(cN/tex)	4.1	4.7	5.2
	Tenacity CV%	20.7	20.2	16.9

yarn has the highest average twist value, it also has the highest twist unevenness, lowest tenacity and the maximum tenacity CV%. The reason is that yarn 1 is in-phase self-twist yarn, in which exists an obvious weak twist area due to the corresponding twist zone and no twist zone. The twist unevenness of yarns 2 and 3 is less than that of yarn 1. Yarns 2 and 3 are phased self-twist yarns. A certain phase difference can make the twistless point misplace a certain distance so as to form a self-twist yarn of two-ply structurein which there is twist on one strand and simultaneously no twist on the other. Thereby the length of the weak twist zone on the self-twist yarn is reduced to improve the yarn tensile properties. From the practical data for 49×2 tex and 113×2 tex in ***Table 2***, the tenacities of yarns 2 and 3 are greater than that of yarn 1, and the tenacity CV% of yarn 2 is less than that of yarn 1. Yarn 3 has maximum breaking tenacity and minimum breaking tenacity CV%.

Conclusions

1. The twist distribution function of self-twist yarn is calculated by two methods: 1. using the difference in distance *c*, and 2. using the twist distribution function of strands A and B, respectively. Then the average twist for a half cycle length is calculated by the twist distribution functions from the two methods above. Comparing the calculation value from the two methods with actual test twists for a half cycle length, the result shows that the calculation value from method 2 is closer to the values measured, namely the twist distribution function derived from the twist distribution function of strands A and B, respectively.
2. The twist unevenness of self-twist yarn is calculated by the twist distribution function from method 2. The twist unevenness of yarn 1 is the highest, and that of yarns 2 and 3 decreases in turn. From the test data of 49×2 tex and 113×2 tex self-twist yarns, in-phase self-twist yarn 1, with higher twist unevenness, has a lower breaking tenacity and higher unevenness of breaking tenacity, and in the same way, phased self-twist yarn 3, with a lower twist unevenness, has a higher breaking tenacity and lower unevenness of breaking tenacity.

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