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Study of Self-twist Distribution Functions in Different Convergence Modes

Abstract
Twist distribution functions of self-twist yarn are examined by calculating the twist distribution functions of two strands from the nip of self-twist rollers to the convergence point in three different convergence modes. Twist distribution curves of three different convergence modes on the half cycle length are presented by the twist distribution functions. The images show that the self-twist yarn with a phase difference has a lower self-twist peak than in-phase self-twist yarn. Thus the existence of a phase difference not only causes a decrease in the self-twist but also a decrease in the length of the weak-twist zone. Furthermore, the value of the phase difference is calculated according to the twist functions of two strands. Compared with the conventional result, that by the method in this paper is closer to the actual length of the zero twist zone.

Key words: *strand, self-twist, convergence mode, twist distribution function, in-phase, phased.*

Symbol meanings

- D - *Reciprocating stroke of self-twist rollers;*
- P - *Perimeter of strand in mm,*
- L_1 - *Distance from the nip of front rollers 1 in main draft zone to the nip 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 D3 (yarn 3),*
- O_1 - *Convergence point of strand A_1 and strand B_1,*
- O_2 - *Convergence point of strand A_2 and strand B_2,*
- O_3 - *Convergence point of strand A_3 and strand B_3,*
- e - *Distance of two strands,*
- X - *Length of one cycle,*
- Z - *delivery length,*
- $T_1(Z)$ - *Twist distribution function on yarn section L_1,*
- $T_2(Z)$ - *Twist distribution function on yarn section L_2,*
- $T_{2A1}(Z)$, $T_{2B1}(Z)$ - *Twist distribution function of strand A_1 and strand B_1 on yarn section L_2,*
- $T_{2A2}(Z)$, $T_{2B2}(Z)$ - *Twist distribution function of strand A_2 and strand B_2 on yarn section L_2,*
- $T_{2A3}(Z)$, $T_{2B3}(Z)$ - *Twist distribution function of strand A_3 and strand B_3 on yarn section L_2,*
- $T_{ST1}(Z)$, $T_{ST2}(Z)$, $T_{ST3}(Z)$ - *Self-twist distribution functions of three convergence modes.*

Introduction

Self-twist spinning has been extensively used in textile industry to produce pure wool or wool and acrylic mixed yarns. So far, the material for self-twist spinning has primarily been acrylic fibre. The higher yarn output and lower production cost give the self-twist spinning technique distinct advantages over the traditional spinning methods. In past research, Henshaw [1, 2] revealed that self-twist yarn is a two-ply structure in which both the strand and plying twists alternate S and Z along the yarn and devised a mechanical model for the self-twist yarn. Ellis and Walls [3] focused their work on the derivation of a formula for strand twist, self-twist and pairing twist. Henshaw [4] investigated the effect of the processing parameters of self-twist spinning on the distribution of the strand twist of in-phase self-twist yarn. The structure and the properties of acrylic were studied in our recent paper [5 - 7]. However, little research was carried out on the study of the calculation of the phase difference.

Phase differences are realised by different convergence modes. When different convergence modes are adopted to make the different distances on the two strands from the nip of self-twist rollers to the convergence guide, the zero-twist point on the strand is displaced a certain distance to give rise to a phase difference. Some maintain that the phase difference of self-twist yarn is the difference in distance. Ellis and Walls obtained better yarn and fabrics properties by experiment when the phase difference was p/5. The phase difference is derived from

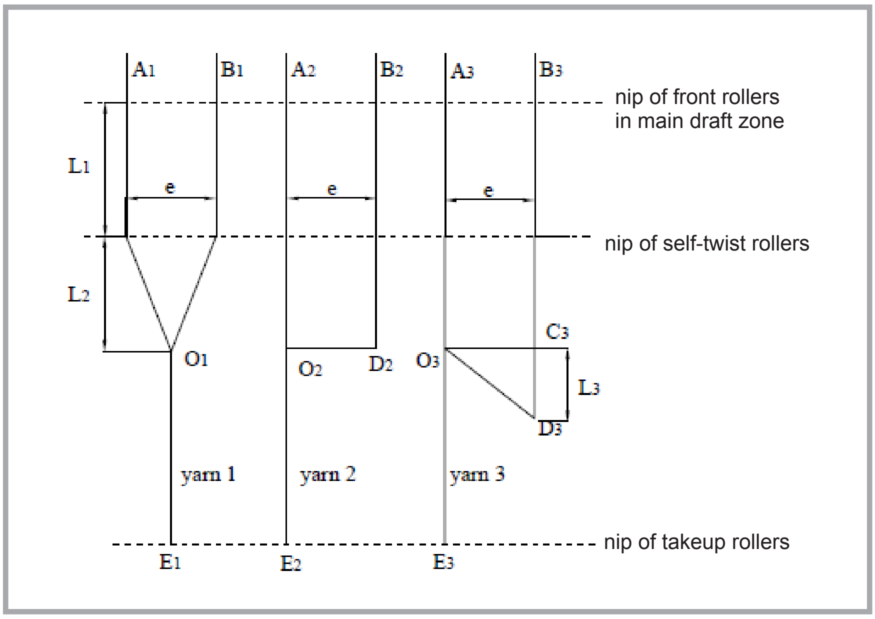

Figure 1. *Schematic diagram of three convergence modes in self-twist yarn;*

the difference in distance. This paper will calculate the phase difference through the different twist distribution functions of two strands so as to get the three different self-twist distribution functions by the method of angle difference.

Twist distribution functions in three convergence modes

Three different convergence modes are shown in ***Figure 1***. Convergence mode 1 is in-phase self-twist yarn, and convergence modes 2 and 3, separately, are phased self-twist yarn 1 and 2. Yarn 1, yarn 2 and yarn 3, respectively, represent in-phase yarn from convergence mode 1, phased yarn 1 - from convergence mode 2 and phased yarn 2 - from convergence mode 3, as shown below. The value of the phase difference can be calculated from the twist distribution function of self-twist yarn. Walls etc. [8, 9] investigated the twist distribution function $T_1(Z)$ of a yarn section from the nip of the front rollers 1 to that of self-twist rollers 2, as well as the twist distribution function $T_2(Z)$ of the yarn section from the nip of self-twist rollers 2 to the convergence point O. $T_1(Z)$ and $T_2(Z)$ are as follows:

Twist distribution function $T_1(Z)$ for yarn section L_1 in an ideal state

The ideal condition refers to the two strands and self-twist yarn keeping uniform motion, with the cross section of two strands and ST yarn being circular (***Equation 1***).

Twist distribution function $T_2(Z)$ for yarn section L_2 in an ideal state: *Equation 2*.

Twist distribution function $T_{2A1}(Z) = T_{2B1}(Z)$ of strand A_1 and strand B_1 for yarn 1 section L_2

The length of strand A_1 and strand B_1 on yarn 1 section L_2 is $\sqrt{\frac{e^2}{4}+L_2^2}$ thus ***Equation 3*** is valid.

Twist distribution function $T_{2A2}(Z)$ of strand A_2 for yarn 2 section L_2 is presented by ***Equation 4***.

Twist distribution function $T_{2B2}(Z)$of strand B_2 for yarn 2 section L_2 is presented by ***Equation 5***.

Twist distribution function $T_{2A3}(Z)$ of strand A_3 for yarn 3 section L_2 is presented by ***Equation 6.***

$$\begin{cases} T_1(Z) = \dfrac{\pi D}{p\sqrt{X^2+4\pi^2 L_1^2}} \sin\left(\dfrac{2\pi Z}{X} - \alpha\right) \\ \alpha = \arctan \dfrac{2\pi L_1}{X} \end{cases} \quad (1)$$

$$\begin{cases} T_2(Z) = \dfrac{2\pi^2 DL_1}{p\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4\pi^2 L_2^2}} \sin\left(\dfrac{2\pi Z}{X} + \beta\right) \\ \beta = \arctan \dfrac{X^2 - 4\pi^2 L_1 L_2}{2pX(L_1+L_2)} \end{cases} \quad (2)$$

$$\begin{cases} T_{2A1}(Z) = T_{2B1}(Z) = \dfrac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}} \sin\left(\dfrac{2\pi Z}{X} - \beta_{A1}\right) \\ \beta_{A1} = \beta_{B1} = \arctan \dfrac{X^2 - 4\pi^2 L_1\sqrt{e^2+4L_2^2}}{2pX(L_1+\sqrt{e^2+4L_2^2})} \end{cases} \quad (3)$$

$$\begin{cases} T_{2A2}(Z) = \dfrac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4\pi^2 L_2^2}} \sin\left(\dfrac{2\pi Z}{X} + \beta_{A2}\right) \\ \beta_{A2} = \arctan \dfrac{X^2 - 4\pi^2 L_1 L_2}{2pX(L_1+L_2)} \end{cases} \quad (4)$$

$$\begin{cases} T_{2B2}(Z) = \dfrac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4p^2(L_2+e)^2}} \sin\left(\dfrac{2\pi Z}{X} + \beta_{B2}\right) \\ \beta_{B2} = \arctan \dfrac{X^2 - 4p^2 L_1(L_2+e)}{2pX(L_1+L_2+e)} \end{cases} \quad (5)$$

$$\begin{cases} T_{2A3}(Z) = \dfrac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4\pi^2 L_2^2}} \sin\left(\dfrac{2\pi Z}{X} + \beta_{A3}\right) \\ \beta_{A3} = \arctan \dfrac{X^2 - 4\pi^2 L_1 L_2}{2pX(L_1+L_2)} \end{cases} \quad (6)$$

$$\begin{cases} T_{2B3}(Z) = \dfrac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4p^2(L_2+L_3+\sqrt{e^2+L_3^2})^2}} \sin\left(\dfrac{2\pi Z}{X} + \beta_{B3}\right) \\ \beta_{B3} = \arctan \dfrac{X^2 - 4p^2 L_1(L_2+L_3+\sqrt{e^2+L_3^2})}{2pX(L_1+L_2+L_3+\sqrt{e^2+L_3^2})} \end{cases} \quad (7)$$

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

By (2)

$$\begin{cases} T_{ST1}(Z) = \dfrac{1}{K}[T_{2A1}(Z) + T_{2B1}(Z)] & T_{2A1}(Z)T_{2B1}(Z) \ge 0 \\ T_{ST1}(Z) = 0 & T_{2A1}(Z)T_{2B1}(Z) < 0 \end{cases} \quad (8)$$

By (3), (4)

$$\begin{cases} T_{ST2}(Z) = \dfrac{1}{K}[T_{2A2}(Z) + T_{2B2}(Z)] & T_{2A2}(Z)T_{2B2}(Z) \ge 0 \\ T_{ST2}(Z) = 0 & T_{2A2}(Z)T_{2B2}(Z) < 0 \end{cases} \quad (9)$$

By (5), (6)

$$\begin{cases} T_{ST3}(Z) = \dfrac{1}{K}[T_{2A3}(Z) + T_{2B3}(Z)] & T_{2A3}(Z)T_{2B3}(Z) \ge 0 \\ T_{ST3}(Z) = 0 & T_{2A3}(Z)T_{2B3}(Z) < 0 \end{cases} \quad (10)$$

Equations: 8, 9 and 10.

Twist distribution function $T_{2B3}(Z)$ of strand B_3 for yarn 2 section L_2 is presented by ***Equation 7*** (see page 27).

Self-twist distribution functions of three convergence modes

Theoretical formula of the relationship between self-twist and strand twist according to the mechanical structure and geometric features are presented by domestic and foreign scholars as follow.

Henshaw [2], an Australia scholar, established the formula (a1):

$$T_{ST} = \frac{1}{6}(T_A + T_B) \qquad (a1)$$

Ellis [3], a British scholar, created the formula (a2):

$$T_{ST} = \frac{1}{2\sqrt{2}}(T_A + T_B) \qquad (a2)$$

Wang [10] wrote the formula (a3):

$$T_{ST} = \frac{1}{3.5}(T_A + T_B) \qquad (a3)$$

Suppose $T_{ST} = \frac{1}{K}(T_A + T_B)$ in formula (a1) K = 6, in formula (a2) K = $2\sqrt{2}$, and in formula (a3) K = 3.5. The results calculated from formulas (al), (a2) &(a3) deviate from the test data for spinning. Since the result of formula (a3) deviates minimally, then, K = $2\sqrt{2}$ is selected.

The Self-twist distribution functions of the three convergence modes are obtained from the twist distribution functions of the strands as follows (see set ***Equation 8, 9 & 10***).

Self-twist distribution function expressions (***Equations 11, 12 & 13***) of the three convergence modes are obtained by going into the twist distribution functions of the strands as ***Equations 11, 12 & 13.***

$$\begin{cases} T_{st1}(Z) = \frac{1}{\sqrt{2}}\left[\frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+\pi^2 e^2+4\pi^2 L_2^2}}\sin\left(\frac{2\pi Z}{X}+\beta_1\right)\right] & T_{2A1}(Z)T_{2B1}(Z) \geq 0 \\ T_{st1}(Z) = 0 & T_{2A1}(Z)T_{2B1}(Z) < 0 \end{cases} \qquad (11)$$

$$\begin{cases} T_{st2}(Z) = \frac{1}{2\sqrt{2}}\left[\frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4\pi^2 L_2^2}}\sin\left(\frac{2\pi Z}{X}+\beta_{A2}\right) + \frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4p^2(L_2+e)^2}}\sin\left(\frac{2\pi Z}{X}+\beta_{B2}\right)\right] & T_{2A2}(Z)T_{2B2}(Z) \geq 0 \\ T_{st2}(Z) = 0 & T_{2A2}(Z)T_{2B2}(Z) < 0 \end{cases} \qquad (12)$$

$$\begin{cases} T_{st3}(Z) = \frac{1}{2\sqrt{2}}\left[\frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4\pi^2 L_2^2}}\sin\left(\frac{2\pi Z}{X}+\beta_{A3}\right) + \frac{2\pi^2 DL_1}{P\sqrt{X^2+4\pi^2 L_1^2}\sqrt{X^2+4p^2(L_2+L_3+\sqrt{e^2+L_3^2})^2}}\sin\left(\frac{2\pi Z}{X}+\beta_{B3}\right)\right] & T_{2A3}(Z)T_{2B3}(Z) \geq 0 \\ T_{st3}(Z) = 0 & T_{2A3}(Z)T_{2B3}(Z) < 0 \end{cases} \qquad (13)$$

Equations 11, 12 and 13.

Self-twist distribution of the three convergence modes for half-cycle length

By substituting the known spinning parameters L_1 = 45 mm, L_2 = 15 mm, P = 0.8857 mm, X = 210 mm, D = 76 mm, e = 19 mm & L_3 = 17 mm in ***Equations 8, 9 & 10***, three self-twist distribution functions of the different convergence modes are obtained by***Equation 14***.

$$\begin{aligned} T_{st1}(Z) &= \frac{1}{\sqrt{2}}\left[9.10\sin\left(\frac{\pi Z}{105}+\frac{8.63\pi}{180}\right)\right] \\ T_{st2}(Z) &= \frac{1}{2\sqrt{2}}\left[9.40\sin\left(\frac{\pi Z}{105}+\frac{12.43\pi}{180}\right)+7.20\sin\left(\frac{\pi Z}{105}-\frac{8.89\pi}{180}\right)\right] \\ T_{st3}(Z) &= \frac{1}{2\sqrt{2}}\left[9.40\sin\left(\frac{\pi Z}{105}+\frac{12.43\pi}{180}\right)+5.20\sin\left(\frac{\pi Z}{105}\;\frac{23.23\pi}{180}\right)\right] \end{aligned} \qquad (14)$$

Equation 14.

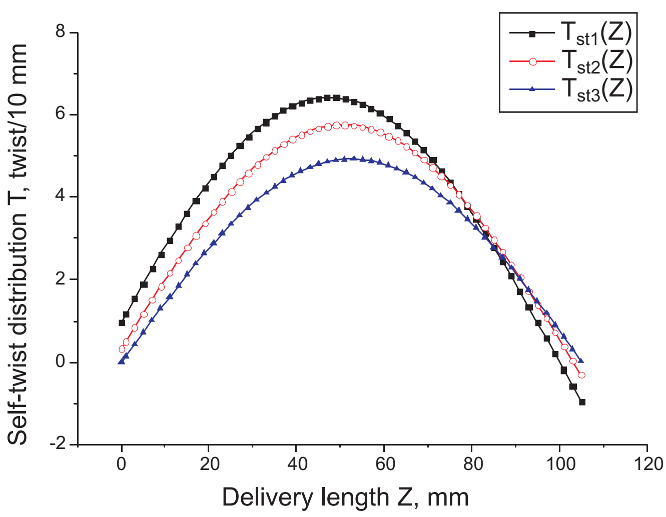

Figure 2. *Twist distribution of different convergence modes for a half cycle.*

Using Matlab to project the three functions above, ***Figure 2*** is obtained.

As shown in ***Figure 2***, the peak maximum of the self-twist distribution of yarn 1 is the highest, and the peak maximum of the self-twist distribution of yarns 2 and 3 is lower than for yarn 1. The reason for the in-phase yarn is that the twist zones and zero-twist zones of the two strands correspond with each other, with a self-twist zone and zero-twist zone being

Table 1. Phase difference from two calculation methods and the actual length of the zero twist z.

Convergence mode	Calculating phase difference		
	Δ_{0i} Distance difference	Δ_i Angle difference	Length of zero twist zone per mm
Yarn 2	31.1	21.3	25.0
Yarn 3	72.9	35.7	34.3

formed. A zero-twist zone on in-phase yarn is the weakest zone with respect to tenacity. In yarns 2 and 3, a certain distance is displaced from the twist zone and the zero-twist zone of the two strands so that a twist zone of one strand meets with the zero-twist zone of another, resulting in not only a decrease in self-twist but also a decrease in the length of the weak-twist zone.

Phase calculation

Calculating the phase difference with a conventional method

The phase difference of in-phase self-twist yarn is zero, therefore it need not be calculated. However, the phase difference of the latter two convergence modes should be calculated.

Conventionally, the phase difference is calculated by multiplying 360º and the ratio between the distance from the nip of the self-twist rollers to the convergence point of the two strands and the length X in one cycle.

Its calculation formula is as follows:

$$\Delta_{0i} = 360^{\circ} \times \frac{c_i}{X} \qquad i = 1,2,3 \qquad (11)$$

The differences in distance of the latter two convergence modes are c_2 = e, $c_3 = L_3 + \sqrt{e^2 \quad L_3^2}$.

Calculating the phase difference with the angle difference method

There exists a certain angle difference between two strands from the derivation of the twist distribution function of the two strands. Hence we will calculate the phase difference from the angle difference.

Its calculation formula is as follows:

$$\Delta_i = \arctan \beta_{Ai} - \arctan \beta_{Bi} \qquad (12)$$

Hence, the phase difference of yarns 2 and 3 are as following:

$$\Delta_2 = \arctan \beta_{A2} - \arctan \beta_{B2} =$$
$$= \arctan \frac{X^2 - 4\pi^2 L_1 L_2}{2pX(L_1 + L_2)} +$$
$$- \arctan \frac{X^2 - 4p^2 L_1 (L_2 + e)}{2\pi X \quad L_1 + L_2 + e}$$

$$\Delta_3 = \arctan \beta_{A3} - \arctan \beta_{B3} =$$
$$= \arctan \frac{X^2 - 4\pi^2 L_1 L_2}{2pX(L_1 + L_2)} +$$
$$- \arctan \frac{X^2 - 4p^2 L_1 (L_2 + L_3 + \sqrt{e^2 + L_3^2})}{2p X (L_1 + L_2 + L_3 + \sqrt{e^2 + L_3^2})}$$

Comparison of the results calculated from the two different methods

The phase difference is calculated by the two methods with actual spinning conditions. The phase difference is formed by the distance of the two strands, which make the position of the zero twist point vary over a certain range. From this point, the length of the zero twist zone should be approximately equal to the phase difference. Upon the substitution of e = 19 mm, X = 210 mm, L_1 = 45 mm, L_2 = 15 mm & L_3 = 17 mm in the formula, we obtain the results shown in ***Table 1*** and can compare the actual length of the zero twist zone of 50 tex wool/acrylic self-twist yarn.

As shown in ***Table 1***, it is obvious that the result of the angle difference put forward in this paper is closer to the length of the zero twist zone.

Conculsion

The twist distribution functions of self-twist yarn are examined by calculating the twist distribution functions of two strands from the nip of self-twist rollers to the convergence point in three different convergence modes. Twist distribution curves of three different convergence modes for a half cycle length are presented by the twist distribution functions. The curves show that self-twist yarn with a phase difference has a lower self-twist peak than in-phase self-twist yarn. Thus the existence of a phase difference not only causes a decrease in self-twist but also a decrease in the length of the weak-twist zone. Furthermore, the value of the phase difference is calculated according to the twist functions of two strands. Compared with the conventional result, that obtained by the method in this paper is closer to the actual length of the zero twist zone.

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