Fiber Orientation and Twists of the Half-Yarn on the Drum Surface in Friction Spinning

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Abstract

In a yarn formation process, twist is a very important yarn factor, and at the same time an important process variable either. The twist is topologically described by the orientation of the constituent fiber orientation, which is usually defined by turns per length or twist angle. But in friction yarn spinning, twist insertion is complicated. In the spinning zone consisting of two drums, the staples are delivered and accumulated around the half yarn surface, while after the friction drum the half yarn undergoes a real twisting operation between the drum exit and the take-up roller. Therefore the twist in the friction yarn is difficult to define.

This study reports on the twist behavior of the half yarn on the friction drum during the yarn forming process. As the twist is directly coupled with the yarn thickness, the dynamic behavior of yarn thickness is taken into account. Therefore a mathematical model, describing the changes of yarn thickness and twist, was established. Introducing a slippage factor between friction drum and half yarn surface, the continuities of fiber mass and twists on the friction drum were c1onsidered. With some assumptions the equation system was simplified and the transient responses of the yarn thickness and twists were simulated numerically by FDM, especially by applying Forward Time Backward Space method.

Dynamic behaviors of yarn thickness showed a saturated exponential form for the step change in the input rate of the fiber fleece. However, twists showed a much complicated way of behavior because of the fiber allocation and real twist effect by radial thickness increase on the friction drum. The fluctuation of the input fiber fleece rate has an influence on the twist distribution through the half yarn thickness change.

Keywords: friction spinning, half yarn, equation of yarn thickness, equation of twist, fiber fleece fluctuation, twist distribution, thickness change.

1. Introduction

The friction spinning, called the all-purpose yarn formation technology, is characterized in high production rate, wide scope of the treatable fiber material, and flexibility to produce engineered yarns. Even though the yarn has theoretically a constant helical angle throughout the yarn diameter, its low tensile strength is the critical weak point. The twist variation and the sensitivity of the yarn properties to the process conditions can attribute to the low strength [1,2,3]. To improve the yarn properties and the process efficiency many efforts were made on the process analysis and optimization [4,5,6], dealing with experimental and some theoretical analyses to find the relationship between specific material properties and process variables, which could hopingly lead the engineers to the solution for the problems that occurred due to the different properties of the friction spun yarn from the conventional yarns. In spite of those efforts, we could not have insight into what takes place during the yarn formation on the friction drum and still have difficulties to maintain the yarn quality if a material parameter or process variable changes during the process. To cope with this problem, a theoretical systemization of the procedure how the fiber fleece is transformed into a bundle on the friction drum is needed. This paper deals with setting up a dynamic model describing the friction yarn formation process, based on the mass continuity and twist conservation.

2. Theories

During friction yarn formation fibers are delivered into the input channel and then dropped onto the drum surface, which transports and stacks the fibers to the fiber bundle rotating between two surfaces moving in opposite directions. While the fibers wrap around the bundle surface, the wrapped fiber bundle (yarn tail) is tugged by the yarn delivery roll. Therefore twists by fiber arrangement are generated. The in-process bundle that rotates between two surfaces can be described schematically as in Fig.1.

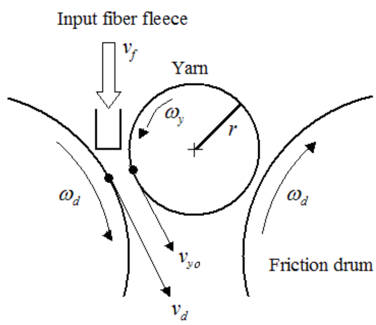


Fig.1 Schematic representation of the friction yarn formation.

The half yarn (in-process bundle) with the radius of r and the angular velocity of ω_y rolls on the friction drums that rotates with the linear velocity v_d. The velocity difference of the surfaces of yarn and drum due to surface slippage can be described, introducing a linear dependence on the drum velocity and the yarn radius, as

$$v_d - v_{yo} \propto (v_d, r) = k_v \cdot v_d - k_r \cdot r$$

The parameter S, called a slippage ratio, is defined as

$$S = \frac{v_d - v_{yo}}{v_d} = k_v - k_r \cdot \frac{r}{v_d}.$$

The slippage ratio is thus dependent on the parameter $\frac{r}{v_d}$, remaining in the range $0 \le S \le 1$.

2.1 Continuity equation

Considering a control volume at x with an infinitesimal distance dx along the bundle axis shown in Fig.2, continuity equation can be derived as follows;

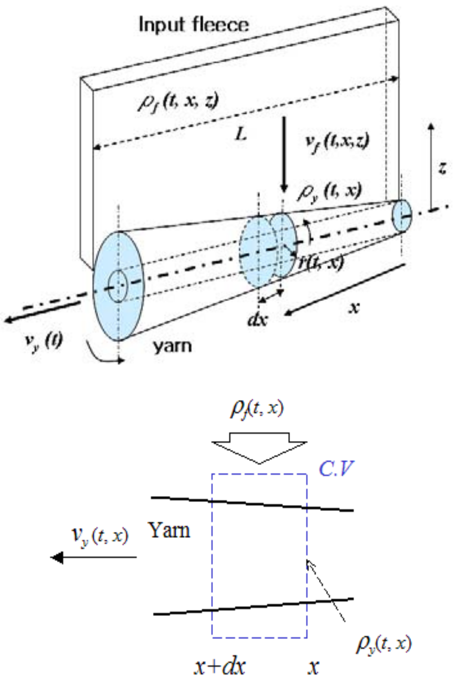


Fig.2 Infinitesimal yarn section in friction spinning.

Change rate of mass in a control volume for an infinitesimally small time dt is

$$\frac{d\{\rho_y(t,x) \cdot A_y(t,x) \cdot dx\}}{dt},$$

where $\rho_y(t,x)$ is the mass density of the half-yarn at (t,x), $A_y(t,x)$ is cross sectional area of the half-yarn at (t,x).

Mass flow rate of the half-yarn at (t,x) denoted by $Q_y(t,x)$ and the mass of the fiber fleece delivered onto the surface of the yarn tail segment dx by $Q_f(t,x)$ can be described as

$$Q_y(t,x) = \rho_y(t,x) \cdot v_y(t,x) \cdot A_y(t,x) \quad \text{and}$$

$$Q_f(t,x) = \rho_f(t,x,0) \cdot v_f(t,x,0) \cdot D(t,x) \cdot dx,$$

where $\rho_f(t,x,0)$ represents the mass density, $v_f(t,x,0)$ the feeding velocity, and $D(t,x)$ the thickness of the input fiber fleece at $(t,x,0)$, respectively.

Total mass flow rate into the control volume at $(t,x,0)$ is

$$Q_y(t,x) + Q_f(t,x) = \rho_y(t,x) \cdot v_y(t,x) \cdot A_y(t,x) + \rho_f(t,x,0) \cdot v_f(t,x,0) \cdot D(t,x) \cdot dx$$

and mass flow rate out through the surface at $(t, x+dx)$ is

$$Q_y(t, x+dx) = \rho_y(t,x+dx) \cdot v_y(t,x+dx) \cdot A_y(t,x+dx).$$

The loss rate of fibers $m(t,x) \cdot dx$ in the yarn segment of dx leads to the mass balance like

$$\frac{d\{\rho_y(t,x) \cdot A_y(t,x) \cdot dx\}}{dt} = -\rho_y(t,x+dx) \cdot v_y(t,x+dx) \cdot A_y(t,x+dx) + \rho_y(t,x) \cdot v_y(t,x) \cdot A_y(t,x) + [\rho_f(t,x) \cdot v_f(t,x) \cdot D(t,x) - m(t,x)] \cdot dx.$$

If the loss rate of fibers is assumed to be proportional to slippage ratio,

$$m(t,x) = k \cdot S = m_0 - \alpha \cdot r(t,x),$$

and ρ_y, ρ_f, and v_f are constants, the mass continuity equation becomes

$$\frac{\partial A_y(t,x)}{\partial t} + \frac{\partial [v_y(t) \cdot A_y(t,x)]}{\partial x} - \frac{\alpha}{\sqrt{\pi} \cdot \rho_y} \cdot \sqrt{A_y(t,x)} = \frac{\rho_f \cdot v_f \cdot D(t,x) - m_0}{\rho_y} \tag{1}$$

2.2 Equation of twists

In this system, the rotating yarn, contacting with the friction drum without any slippage, has the same linear velocity along the yarn axis, which generates different angular velocities depending on the yarn radius. It means twists insertion into the yarn changes even in the yarn formation process due to different yarn rotations according to the yarn thickness.

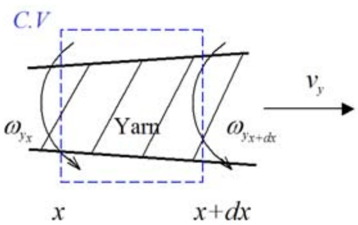


Fig.3 The twisting model of a yarn

Considering a control volume shown in Fig. 3, twist flow in at (t,x) can be written by

$$Q_T(t,x)=\frac{T(t,x)\cdot dx}{dt}=T(t,x)\cdot {dx}/{dt}=T(t,x)\cdot v_y(t,x)$$

(T=twist (turns per unit length))

In the same way, twist flow out at $(t, x+dx)$ is given as

$$Q_T(t,x+dx)=\frac{T(t,x+dx)\cdot dx}{dt}$$
$$=T(t,x+dx)\cdot {dx}/{dt}=T(t,x+dx)\cdot v_y(t,x+dx)$$

Therefore the total twist change rate on the friction drum at (t,x) is

$$\frac{d\{T(t,x)\cdot dx\}}{dt}=-(Q_T(t,x+dx)-Q_T(t,x))+\omega_y(t,x+dx)-\omega_y(t,x)$$
$$=-T(t,x+dx)\cdot v_y(t,x+dx)+T(t,x)\cdot v_y(t,x)$$
$$+\omega_y(t,x+dx)-\omega_y(t,x)$$

or simplification yields

$$\frac{\partial T(t,x)}{\partial t}=-\frac{\partial\{T(t,x)\cdot v_y(t,x)\}}{\partial x}+\frac{\partial\omega_y(t,x)}{\partial x}$$

Since $r_y(t,x)\cdot\omega_y(t,x)=\omega_d(t,x)\cdot r_d(t,x)\cdot(1-S)$, thus

$$\omega_y(t,x)=\frac{\omega_d(t,x)\cdot r_d(t,x)\cdot(1-S)}{r_y(t,x)}=v_d(t)\cdot(1-S)\sqrt{\frac{\pi}{A_y(t,x)}}$$

Therefore for S=0 we can write the twist equation as

$$\frac{\partial T(t,x)}{\partial t}=-v_y(t)\cdot\frac{\partial T(t,x)}{\partial x}+\frac{\partial\omega_y(t,x)}{\partial x} \tag{2}$$
$$=-v_y(t)\cdot\frac{\partial T(t,x)}{\partial x}+v_d(t)\cdot(1-S)\cdot\frac{\partial}{\partial x}\left\{\sqrt{\frac{\pi}{A_y(t,x)}}\right\}$$

where $\omega_y(t,x)$ and $A_y(t,x)$ is the rotational speed and the cross-sectional area of yarn segment at (t,x), respectively.

The twist in a yarn might be in the *S* (right hand) or *Z* (left hand) direction. Fig. 3 represents the *S*-twist yarn. We define twist in the *Z* direction as positive twist (T>0) and that in the *S* direction as negative twist (T<0)

3. Simulation

Given the theoretical model (equation 1), analysis about the dynamic characteristics of the friction yarn formation process can be performed. The friction process can then be understood as a system, where the variables that cause the change of the process states are fleece thickness $D(t,x)$ and yarn delivery speed $v_y(t)$, which we can change deliberately, while the output yarn radius can be taken as a response variable. The system concept for analyzing the friction spinning can be summarized as Fig. 4.

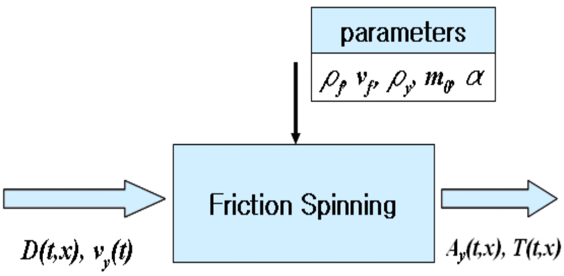


Fig.4 Description of the friction process as a system.

As equations 1 and 2 imply, the dynamics of the friction yarn formation is described by a nonlinear partial differential equations system, the solution of which is not to obtain analytically.

Fundamental equations that describe the thickness variation and the twist flow of yarn in a spinning zone can be solved by a numerical method. We use the Finite Difference Method(FDM), particularly, the Forward-Time and Backward-Space(FTBS) formula with an explicit scheme. Then, the partial differential equations can yield to algebraic equations as shown in Equations 3 and 4 and be solved under given initial and boundary conditions in an iterative fashion.

$$A_y(i+1,j)=\frac{\Delta t}{\rho_y}\cdot\left[-\rho_y\cdot v_y\cdot\frac{A_y(i,j)-A_y(i,j-1)}{\Delta x}+\rho_f\cdot v_f\cdot D(i)\right]$$
$$+A_y(i,j) \tag{3}$$

$$T(i+1,j)=\frac{\Delta t}{\Delta x}\cdot(\omega_y(i,j)-\omega_y(i,j-1))$$
$$-\frac{\Delta t}{\Delta x}\cdot v_y\cdot(T(i,j)-T(i,j-1))+T(i,j) \tag{4}$$

where $\omega_y(i,j)=v_d(t)\cdot(1-S)\cdot\sqrt{\frac{\pi}{A_y(i,j)}}$.

$M(i,j)$ stands for the variable at time $t=i\cdot\Delta t$ and position $x=j\cdot\Delta x$.

For simulation of the process dynamics we choose a test signal: step signal, as given in Fig.5, while the variables are taken to be dependent only on the time. The fiber loss during fiber accumulation on the friction drum is to be neglected in order to grasp an easier insight in the dynamic characteristics.

Under the conditions given in Table 1, the distribution of the cross-sectional area of the in-process bundle in response to the change of the input fleece thickness and the yarn delivery speed are simulated.

Table 1. Process conditions for simulation

v_f (mm/s)	v_y (mm/s)	r_o (mm)	L (mm)	D_0 (mm)
50 **100** 150	2,000 **2,500** 3,000	0.1	90	0.1

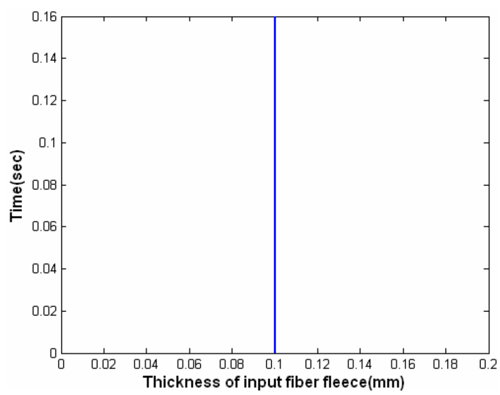


Fig.5 Thickness of input fiber fleece

4. Results and Discussions

4.1 Transient step response of the cross-sectional area

Fig.6 shows a simulation result about the response of the cross-sectional area of the yarn on the friction drum to the step change of the fleece input in 3-D fashion, while the initial yarn thickness is assumed to be constant along the yarn axis. There is a cross-sectional area distribution of the in-process bundle in the yarn formation zone. At the beginning of the process the fibers accumulate on the yarn tail uniformly along the yarn axis, but with the process advance the yarn part that is already fed with fiber fleece moves forward in the yarn delivery direction. Considering a control yarn section that moves with the take–up speed, as the fiber fleece input flow continues, the control yarn section becomes thicker, while its position changes. The fiber accumulation can thus take place until the control yarn section leaves the friction drum.

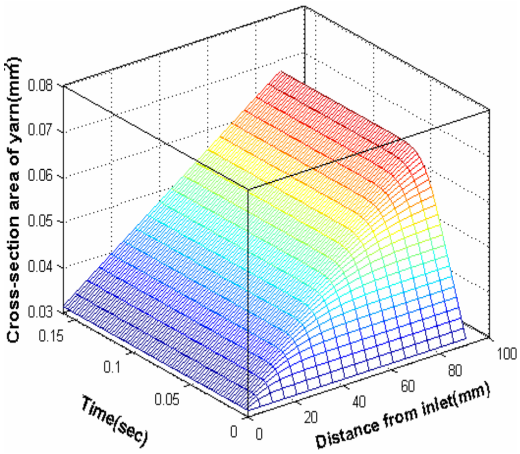
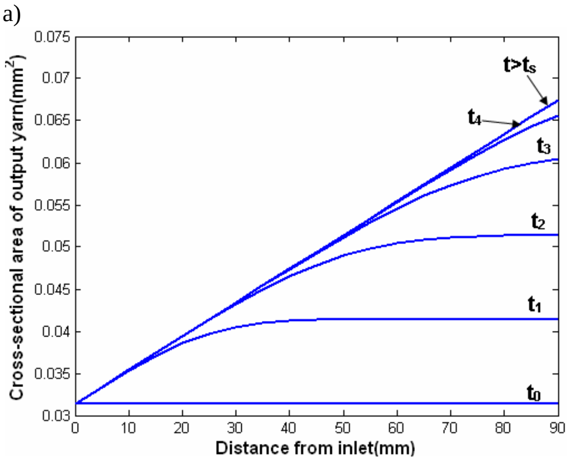


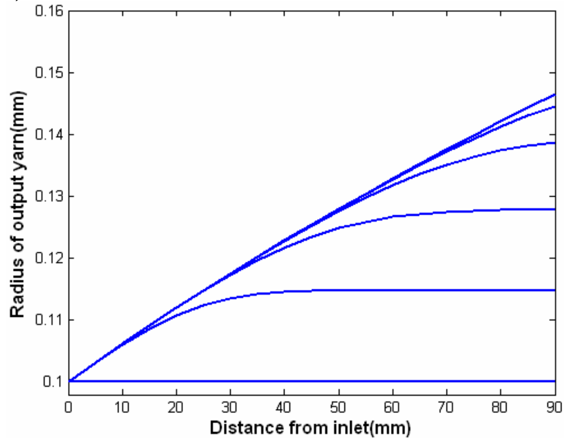
Fig.6 Response of cross-sectional area of in-process bundle to step input thickness.

Therefore when the cross-sectional area distribution on the drum surface is considered at a time point, the distribution should have the form as given in Fig.7. Fig. 7a shows that the cross-sectional area of the in-process bundle increases linearly along the drum axis and from a certain position up its increase slows down and arrives at a constant distribution. But if this slow down of the cross-sectional area along the drum axis can not be large enough for arriving at a constant distribution at another time point, as time goes on further, the yarn cross-section distribution begins to reveal a non-continuous change at the drum exit.

a)



b)



c)

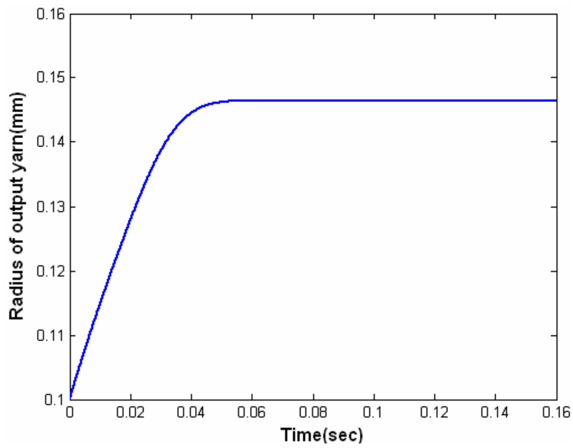


Fig.7 Response of the in-process bundle for a step input of the fleece

a) cross-sectional area distribution on the drum surface
b) radius profiles on the drum surface
c) cross-sectional area profile at the drum exit with time.

After the time period t_d, in which the yarn tail end that has been generated at the process beginning arrives at the drum exit, the cross-sectional distribution versus the position has a shape like a straight line inside the friction drum zone and a constant horizontal line in the zone after the drum. Fig.7b shows the radius profiles of the in-process bundle. The fact that the yarn tail on the drum surface has a linearly increasing cross-sectional area means a curve shape of the radius increase of the yarn tail on the drum surface. As seen in Fig.7b, the shape of the yarn tail tip has even more a blunt figure than a linear pencil-like sharp tip that most of researchers use for explaining the fiber arrangement in the friction yarn tail.

In the time domain for a fixed position on the friction drum, the cross-sectional area of the in-process bundle increases almost linearly with time. That is, the stack of fibers on the in-process bundle surface at the beginning leads to a linear increase of the cross-sectional area. Then, the cross-sectional area arrives at a saturation state, while approaching zero rate of the cross-sectional area increase. The dynamic behavior of the cross-sectional area of the in-process bundle at the drum exit is given in Fig.7c, which shows that the cross-sectional area can be characterized as a slightly deviated 1st order system with an initially linear up-rise. Also the yarn delivery speed affects the output yarn. As the yarn delivery speed increases, the output yarn thickness in cross-sectional area increases linearly at the moment of input change, while the input fleece thickness is held constant.

4.2 Response of the twists to the step change of the input fleece thickness

As shown in equation (2) or (4), twists on the friction drum by the rotational difference of the cross-sections at neighboring positions, so called torque twists on the friction drum, are dependent on the corresponding cross-sectional area. Since the cross-sectional area behavior and distributions have already been obtained, the torque twists can be determined. Fig. 8 shows the simulation results for the step change of the input fleece thickness. Twists for a given time point in the transient state have a basin form profiles. At the position where the input fibers start accumulating, twists are inserted, while around the exit the torque twists are not generated. But in the steady state, the twists inserted are accumulated. As the half-yarn moves forward to exit the friction drum, the total torque twists increase. On the other hand, for a given position it takes a delay time for the half-yarn to arrive at the position. Then, twists begin to build up because the half-yarn radius profile takes place. When a steady state is arrived, twist profile remains constant.

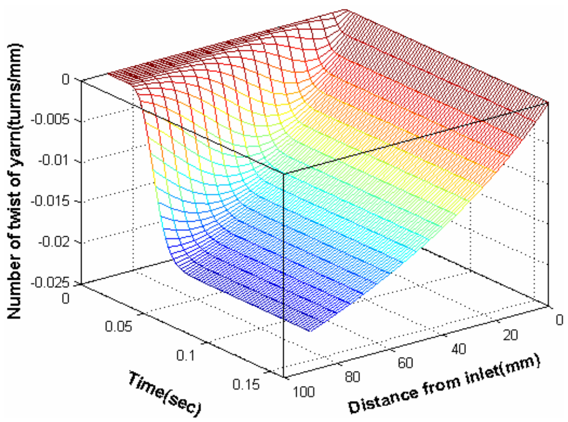


Fig.8 Response of the twists of in-process bundle to step input thickness.

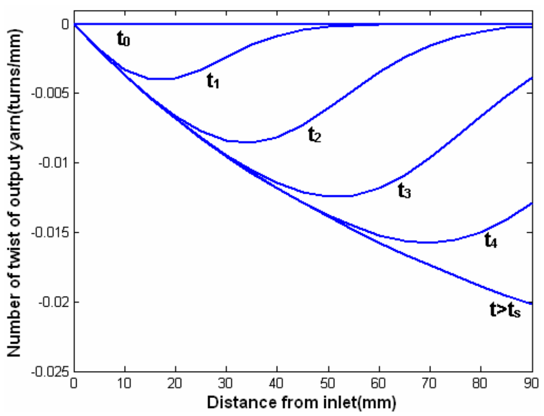


Fig.9 Transient behavior of the in-process bundle twists at various time points for a step input thickness.

Fig. 9 regenerates the twist profile for various time points. From the point of the position on the friction drum twists inserted increase at start point but turn back zero where the input fibers are still not accumulated to cause a radius difference. As fibers are piled and the radius slope of the half-yarn becomes larger, more twists are inserted. Then, at the exit of the friction drum, the half-yarn twists change, as time elapses.

Fig. 10 shows the twist behavior of the in-process bundle at the exit. Initially twists are slowly increased, and then, accelerated. After the transient state the twist reaches a steady state value. This behavior is comparable with the dynamic characteristics of the 2nd order system. As the feeding speed of the input fleece increases, the more torque twists are inserted into the half-yarn in the steady state

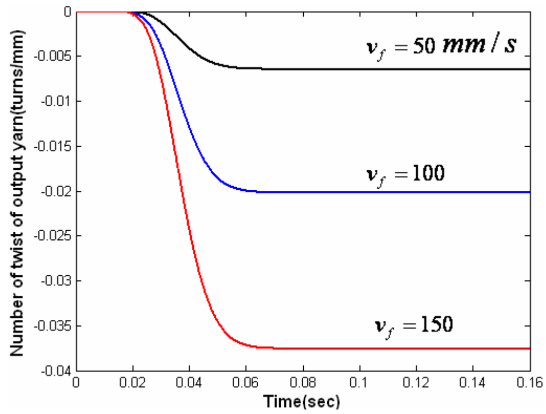


Fig.10 Response of the twists of output bundle to step input thickness.

4.3 Response of the twists to the step change of the yarn delivery speed

When all the process conditions are maintained constant, the torque twists of the half-yarn at the exit can be influenced by the yarn delivery speed. Fig. 11 shows the dynamics of the twists for various delivery speeds.

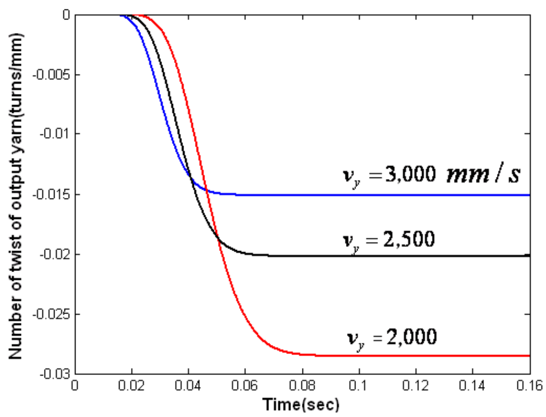


Fig.11 Response of the twists of in-process bundle to the step change of the yarn delivery speed.

The step response of the twists to the step change of the input fleece thickness shows the same type of the dynamics as the 2nd order system. But the steady-state torque twists become less, as the yarn delivery speed increases, whereas the time required getting to the steady state becomes longer. This result means that the higher yarn delivery speed leads to a lower radius change with respect to position, which ends up to a lower level of twists. The slope of the twist change during the transient state, however, is kept unchanged.

5. Conclusions

In this research a mathematical model has been derived, which describes the dynamic behavior of the half yarn structure on the friction drum, that is, half yarn radius and the twist. To confirm the model we used a step test signal for the input fleece thickness change, while the fleece input speed and the yarn delivery speed are taken into consideration. Simulation results show that the indicial response based on the theoretical model showed a good coincidence with what can be expected from the industrial experience, which implies a good correspondence to the reality. Dynamic behavior of yarn thickness was similar to that of a 1^{s}-order-system, but the twist dynamics of the output half yarn show the same characteristic response as the 2^{nd} order system does. From the point of the position on the friction drum, however, twists inserted increase at the starting point but can turn back zero, depending on the radius difference slope. As the radius slope of the half-yarn with respect to position becomes larger, more twists are inserted.

As the yarn delivery speed increases, the steady-state torque twists become less, whereas the time required getting to the steady state becomes longer. The slope of the twist change during the transient state, however, is kept unchanged.

Acknowledgements

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