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INVESTIGATION OF TWIST WAVES DISTRIBUTION ALONG STRUCTURALLY NONUNIFORM YARN

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Abstract:

This paper presents the features of yarn structure formation on spinning machine, i.e. yarn twist change when winding. It was considered that the twist distribution was one of the reasons for its decrease along the formed yarn. In this paper, based on analysis of changes in thickness and twist due to axial deformation, we consider a yarn moving at constant speed. Moving dynamics of yarn are studied here by using Euler variables. The correspondences of forward and reverse twist waves' distribution speeds on presented frequency at various vibration forms are obtained. The parameters of Doppler effect for the waves distributed along the yarn are determined.

Keywords:

Yarn structure, yarn twist, twist distribution, thickness, twist waves.

1. Introduction

Analysis of research literature indicates that the structure of yarn depends on technological and kinematic factors. Structure control, i.e., ways to reduce twist loss and twist distribution along the yarn, and the methods of density regulation are not considered. It is a big problem as characteristics and quality of yarn depend on it. We consider the change in torsion quantity on a ring spinning machine. Formed yarn gets one twist per one turn of the runner. The number of coiled yarn twists changes depending on coil diameter. So, with an increase in diameter of winding, a larger twist occurred. Practice has shown that when twisting the yarn into a coil with a larger and smaller diameters, the difference is about 1% [1]. Twist unevenness also occurs due to vertical movement of the ring bar at a certain distance. So, for example, when lowering the ring strip, a shorter yarn is wound on the package because a part of its length is not wound due to increasing cylinder height. Therefore, in practice, it is used the average twist obtained when the number of torsions in any section of yarn divided by its length. In this case, appearance of twist irregularities is not taken into account, as it is very important for uniform yarn structure. In well-known papers [2–17], the roughness in twist is not analyzed, i.e., the conditions for formation of structure, on which the quality indicators of yarn obtained by the spinning machine are largely dependent, are not taken into account. As noted above, the difference in the number of yarn twist segments leads to appearance of twists in short sections when the annular strip moves up and down. Uniformity of twist distribution in this case depends on the spinning method, i.e., a twist along the yarn is distributed differently. Investigations of these issues are described in papers [2, 5–10]. On yarn twist distribution at different spinning methods, the positive results were obtained. A number of works are about the study of twist distribution in OE yarn [11–15]. The issue of twist distribution in the modified yarn was also studied [7]. In all papers, the process of twist wave distribution along the yarn is considered. In this case, the distribution of shear deformations occurs both along the axis of the yarn and along the radial direction. For twist distribution along the yarn, the structural unevenness is important. Twist distribution has been sufficiently investigated, but, as a rule, a structurally uniform and homogeneous product is considered, while the structure of the product is not considered. Therefore, twist distribution with such shortcomings is investigated in this paper.

2. Theory

In paper [5, 6] considered twist distribution of the yarn with structural unevenness where applied the generalized law for Hooke's anisotropic medium, according to which the correspondences between the components of the stress and strain tensors in ax symmetric coordinates are represented by five elastic constants [7].

$$\sigma_{zz} = a_c\varepsilon_{zz} + b_c(\varepsilon_{rr} + \varepsilon_{\theta\theta}), \quad \sigma_{rr} = b_c\varepsilon_{zz} + c_c\varepsilon_{rr} + d_c\varepsilon_{\theta\theta},$$

$$\sigma_{\theta\theta} = b_c\varepsilon_{zz} + d_c\varepsilon_{rr} + c_c\varepsilon_{\theta\theta}, \; \sigma_{rz} = G\varepsilon_{rz} \quad \sigma_{z\theta} = G\varepsilon_{z\theta},$$

$$\sigma_{r\theta} = \frac{E_2}{1+\upsilon_{23}}\varepsilon_{r\theta} \tag{1}$$

$$a_c = \frac{(1-\upsilon_{32})E_r^{\,2}}{\Delta}\ ; \quad b_c = \frac{\upsilon_{12}E_1E_2}{\Delta}\ ; \quad c_c = \frac{(E_1-\upsilon_{12}{}^2E_2)E_2}{(1+\upsilon_{32})\Delta}\ ;$$

$$d_c = \frac{(\upsilon_{12}{}^2E_1+\upsilon_{32}E_1)E_2}{(1+\upsilon_{32})\Delta} \qquad \Delta = E_1(1-\upsilon_{32})-2\upsilon_{12}{}^2E_2$$

where σ_{rr}, σ_{zz}, $\sigma_{\theta\theta}$, σ_{rz}, $\sigma_{z\theta}$, and $\sigma_{r\theta}$ are axial, radial, ring, and shear stresses and ε_{rr}, ε_{zz}, $\varepsilon_{\theta\theta}$, ε_{rz}, $\varepsilon_{z\theta}$, and $\varepsilon_{r\theta}$ are corresponding deformations in coordinates $r0z$, where axis $0z$ is directed along the axis of the yarn, and axis $0r$ is perpendicular to it, and the origin of coordinates is at point O (0,0) (Figure 1). Moreover, E_1 and E_2 correspond the Young's modulus along axial directions $0z$ and $0r$, respectively, and υ_{12} and υ_{32} are corresponding Poisson's ratios, characterized by a change in yarn thickness and twist due to axial deformation G -modulus of planar rigidity $(z\theta)$.

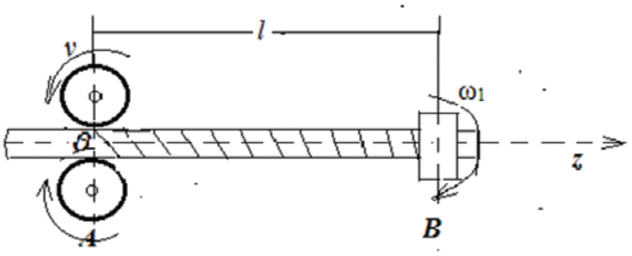

Figure 1. Scheme of the yarn twisting process.

We denote the angular displacement of yarn arbitrary section by $u_\theta = u(r,z,t) = r\theta(r,z,t)$ and consider the remaining components of the displacement vector to be equal to zero.

We denote the angular displacement of yarn arbitrary section by $u_\theta = u(r,z,t) -$, and the remaining components of the displacement vector are assumed to be zero; then, the components of the strain tensor will be expressed by using the following equation:

$$\varepsilon_{\theta z} = \frac{\partial u}{\partial z}\ ; \ \varepsilon_{r\theta} = \frac{du}{dr} - \frac{u}{r} \tag{2}$$

In Eq. (2), we see that deformation shifts $\varepsilon_{\theta z}$ and $\varepsilon_{r\theta}$ are linearly depend on displacement $u(r,z,t)$ and its derivative. In an adopted scheme, the motion equation is as follows:

$$\rho\frac{\partial^2 u}{\partial t^2} = \frac{2\sigma_{r\theta}}{r} + \frac{\partial\sigma_{r\theta}}{\partial r} + \frac{\partial\sigma_{z\theta}}{\partial z} \tag{3}$$

after substitution of $\sigma_{z\theta}$ and $\sigma_{r\theta}$ from Eq. (1), the Eq. (3) takes the following form:

$$\rho\frac{\partial^2 u}{\partial t^2} = \frac{E_2}{1+\upsilon_{32}}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2}\right) + G\frac{\partial^2 u}{\partial z^2} \tag{4}$$

Eq. (4) describes the distribution of twisting waves along the yarn with a structurally heterogeneous property. In this case, the twist changes both along the axis of the yarn and along the radial direction. We consider a yarn with radius r_0 and final length l, sliding at constant speed v on positive direction of axis $0z$. It is more convenient to study the dynamics of a moving yarn in Euler variables. Therefore, passing from total time derivatives to a local one, we obtain the following equation:

$$\frac{\partial^2 u}{\partial t^2} + 2v\frac{\partial^2 u}{\partial t\partial z} + v^2\frac{\partial^2 u}{\partial z^2} = \frac{a_2^2}{1+\mathrm{u}_{32}}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2}\right) + b^2\frac{\partial^2 u}{\partial z^2} \tag{5}$$

where $a_2 = \sqrt{\frac{E_2}{\mathrm{r}}}$ is the speed of cylindrical wave distribution and $b = \sqrt{\frac{G}{\rho}}$ is the speed of twist wave distribution. We consider the process of formation and propagation of stationary wave processes in a yarn, a side surface that is free from tangential forces:

$$\sigma_{ro} = G\left(\frac{\partial u}{\partial r} - \frac{u}{r}\right) = 0 \quad \text{at } r = r_0 \tag{6}$$

For yarn axis, the displacement roundedness condition is applied:

$$u = 0 \ \text{ at } r = 0 \tag{7}$$

Yarn initial cross section A in Euler's variable is inactive, i.e.,

$$u = 0 \ \text{ at } z = 0 \tag{8}$$

Full angular speed of the yarn in a cross section B will be equal to the following equation:

$$\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial z}\right)u(r,z,t) = \omega_* e^{i\omega e} \quad \text{at } z = l \tag{9}$$

where ω_* is the angular speed of the twisting part.

The solution for Eq. (5) satisfying the boundary conditions of Eqs (6) and (7) can be represented as follows:

$$u = \sum_{n=1}^{\infty} W_n(z,t)R_n(r) \tag{10}$$

where function $R_n(r)$ satisfied the following equation

$$R_n'' + \frac{1}{r}R_n' - \frac{1}{r^2}R_n = -\lambda_n^2 R_n \tag{11}$$

and according to Eqs (9) and (10) the boundary conditions are

$$R_n' - \frac{1}{r}R_n = 0 \ \text{at } r = r_0 \tag{12}$$

$$R_n = 0 \ \text{at } r = 0 \tag{13}$$

The solution of Eq. (11) is represented through the first-order Bessel function, $R_n = J_1(\lambda_n x)$ $\lambda_n -$ equation roots: $J_0(\lambda_n r_0)(\lambda_n^2 r_0^2 - 1) - \lambda_n r_0 J_1(\lambda_n r_0) = 0$, where $J_0(x)$ is the zero order of Bessel function. Putting the expression $u(r,z,t)$ from Eq. (10) to Eq. (5) and taking into consideration Eq. (11), we obtain the following equation:

$$\sum_{n=1}^{\infty}\left(\frac{\partial^2 W_n}{\partial t^2}+2v\frac{\partial^2 W_n}{\partial z\partial t}+(v^2-b^2)\frac{\partial^2 W_n}{\partial z^2}+a^2\lambda_n^2 W_n\right)R_n = 0$$

Using the condition of orthogonality $\int_0^{r_0} rR_n(r)R_k(r)dr = 0$ at $n \neq k$, we obtain the following equation:

$$\frac{\partial^2 W_n}{\partial t^2}+2v\frac{\partial^2 W_n}{\partial z\partial t}+(v^2-b^2)\frac{\partial^2 W_n}{\partial z^2}+a^2\lambda_n^2 W_n = 0,$$

$$n = 1,2,3... \qquad (14)$$

where $a=\sqrt{E_2/\rho(1+\upsilon_{32})}$.

Eq. (12) for known values of characteristic numbers λ_n describes the process of monochromatic twist wave distribution along the yarn. The matter of no twist change in a radial direction corresponding to a zero form of fluctuations with $\lambda_1 = 0$ is considered in the paper [11].

The solution of Eq. (14) is represented as follows:

$$W_n = y_n(z)e^{iwt}$$

Function $u(r,z,t)$ has the following form:

$$u=\sum_{n=1}^{\infty} y_n(z)R_n(r)e^{iwt} \qquad (15)$$

where functions $y_n(z)$ satisfy the equations

$$(v^2-b^2)y_n''+2v\omega i y_n'+(a^2\lambda_n^2-\omega^2 y_n=0) \qquad (16)$$

and according to Eqs (7) and (9) satisfy the following conditions

$$y_n(0)=0 \qquad (17)$$

$$v y_n'(l)+i\omega y_n(l)=p_n\omega_* \qquad (18)$$

where $p_n=\dfrac{\int_0^{r_0} rJ_1(\lambda_n r)dr}{\int_0^{r_0} rJ_1^2(\lambda_n r)dr}$

We consider the case $v > b$ and solution for Eq. (16). Taking Eq. (17) into consideration, it will be represented as follows:

$$y_n = A_n[\exp(i\alpha_{1n}z)-\exp(i\alpha_{2n}z)]$$

where

$$\alpha_{1n}=\frac{\sqrt{b^2\omega^2+a^2\lambda_n^2(v^2-b^2)}-v\omega}{v^2-b^2},$$

$$\alpha_{2n}=-\frac{\sqrt{b^2\omega^2+a^2\lambda_n^2(v^2-b^2)}+v\omega}{v^2-b^2} \qquad (19)$$

$A_n = A_{1n}+iA_{2n}$ is a complex constant, the component of which is determined from conditions of Eq. (18)

$$A_{1n}=\omega_* p_n\frac{\Delta_{2n}(\omega)}{\Delta_n(\omega)}, \qquad A_{1n}=-\omega_* p_n\frac{\Delta_{1n}(\omega)}{\Delta_n(\omega)},$$

$$\Delta_n=\Delta_{1n}^2(\omega)+\Delta_{2n}^2(\omega)$$

$$\Delta_{1n}=(\alpha_{1n}v+\omega)\cos\alpha_{1n}l-(\alpha_{2n}v+\omega)\cos\alpha_{2n}l,$$

$$\Delta_{2n}=(\alpha_{1n}v+\omega)\sin\alpha_{1n}l-(\alpha_{2n}v+\omega)\sin\alpha_{2n}l$$

Thus, the angular movement of the yarn between sections A and B can be represented as follows:

$$u=\sum_{n=1}^{\infty}(A_{1n}+iA_{2n})[\exp i(\omega t+\alpha_{1n}z)-\exp i(\omega t+\alpha_{2n}z)]R_n(r)=\sum_{n=1}^{\infty}[u_{1n}(z,t)+iu_{2n}(z,t)]R_n(r) \qquad (20)$$

where

$$u_{1n}=A_{1n}[\cos(\omega t+\alpha_{1n}z)-\cos(\omega t+\alpha_2 z)]-A_{2n}[\sin(\omega t+\alpha_{1n}z)-\sin(\omega t+\alpha_{2n}z)]$$

$$u_{2n}=A_{1n}[\sin(\omega t+\alpha_{1n}z)-\sin(\omega t+\alpha_{2n}z)]+A_{2n}[\cos(\omega t+\alpha_{1n}z)-\cos(\omega t+\alpha_{2n}z)]$$

As seen in Eq. (19), the values α_{1n} and α_{2n} are positive ($\alpha_{1n} > 0$) and negative ($\alpha_{2n} < 0$) numbers accordingly. They are the wave numbers corresponding to various forms of fluctuations on variable r and describing the wave distribution along positive and negative directions of axis $0z$ with speeds $c_{1n}=-\omega/\alpha_{2n}(\omega)$ and $c_{2n}=-\omega/\alpha_{1n}(\omega)$ accordingly. Here, the speeds of waves depend on frequency ω, which indicates the presence of wave dispersion.

If we do not take into account the twist changes in radial direction, then from Eq. (14), we obtain the expressions for the wave numbers as given in the study by Xu et al [10].

$$\alpha_{n1}=k_1=\frac{\omega}{b-v}, \qquad \alpha_{2n}=k_2=-\frac{\omega}{b+v}$$

Moreover, the wave numbers k_1 and k_2 indicate the wave distribution along positive and negative directions of axis $0z$, with the speeds $b+v$ and $v-b$, associated with Doppler effect accordingly. From Eq. (19), it is seen that each eigen value λ_n corresponds to the distribution speeds $c_{1n}(\omega)$ and $c_{2n}(\omega)$, which depend on frequency ω, i.e., as the wave dispersion effect occurs.For wave distribution speeds,

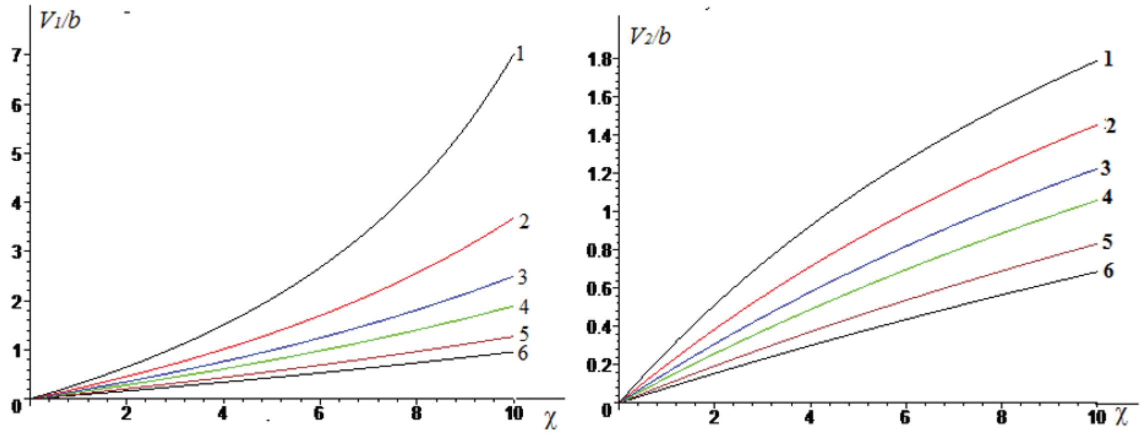

Figure 2. Dependences of backward (a) and direct (b) wave distribution speed on reduced frequency χ at different forms of fluctuations. $1-n=3$, $2-n=4$, $3-n=5$, $4-n=6$, $5-n=8$, $6-n=10$.

using the dimensionless values $\chi = \omega r_0 / b$, $\bar{\lambda}_n = \lambda_n r_0$, $\bar{v} = v / b$, and $\sigma = a / b$, we obtain the following equation:

$$V_{1n} / b = -\frac{\chi(\bar{v}^2 - 1)}{\sqrt{\chi^2 + \sigma^2 \bar{\lambda}_n^2 (\bar{v}^2 - 1)} - \chi \bar{v}},$$

$$V_{2n} / b = \frac{\chi(\bar{v}^2 - 1)}{\sqrt{\chi^2 + \sigma^2 \bar{\lambda}_n^2 (\bar{v}^2 - 1)} + \chi \bar{v}}$$

Figure 2 presented the curves of V_{1n} and V_{2n} speed dependence (referred to shear wave speed b) on dimensionless frequency $\chi = \omega r_0 / b$. The calculations were performed for the following values:

$$E_2 = 0.135 \cdot 10^7 \, Pa, \quad G = 5.55 \cdot 10^4 \, Pa, \quad \upsilon_{32} = 0.5, \quad \bar{v} = 5$$

The analysis of curves shows that Doppler effect for waves distributing along the yarns is held for each fluctuation form of the yarn by its thickness. In this case, the Doppler effect for the backward wave is stronger than that for the direct one. This is due to the processes of wave's reflection from the axis of the yarn.

4. Conclusion

The conditions for distribution of twist waves for a moving yarn with a constant speed are studied, and the parameters of Doppler effect for waves that are distributed along the yarn are determined. It was found that the Doppler effect for the backward wave is stronger than that for the direct one for 3.5 times. This is due to the processes of wave's reflection from yarn axis.

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Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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