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Calculation of Peak Yarn Tension During Ring-Spinning[1]

Introduction

In ring spinning machines a yarn is formed by twisting a train of fibers emitted from a series of drafting roll pairs. The yarn goes successively (see Fig. 1) from the last (front) pair of drafting rolls, through a threaded guide, through a free balloon region, through a traveler, across the space between the ring circumference and the bobbin, to be wound on a bobbin. The traveler is mounted on the ring and rotates around the ring, pulled by the yarn segment attached to the spinning bobbin. A turn of twist is inserted into the fiber train above the traveler by each revolution of the traveler. The delivery speed of the fiber train from the front rolls is slow in comparison to the rotational speed of the bobbin and traveler and thus several turns of twist may be inserted per centimeter of yarn formed.

End breakage and consequently an interruption of production results during ring spinning when the tension in the yarn being formed exceeds the strength of the strand. The yarn being formed is generally the weakest in the region nearest the drafting rollers as this section of the yarn has the least twist. It is therefore desirable to predict and control the tension of the yarn in the region between the thread guide and the front drafting rollers.

Most spinning frames are constructed such that the centerline of the spindle and thread guide is vertical but the location of the exit of the strand from the front drafting rollers is not directly over the centerline of the spindle and thread guide. Typically, the rollers are offset from this centerline such that the yarn in the region between the thread guide and the front rollers is inclined at a fairly significant angle with respect to this vertical centerline. A result of this offset is that the angle of wrap of the yarn around the thread guide is dependent upon the rotational position of the balloon, with a larger angle of wrap when the yarn in the balloon region is on the same side of the thread guide as the drafting rollers and least when on the opposite side. Since the friction of the yarn in passing over the thread guide

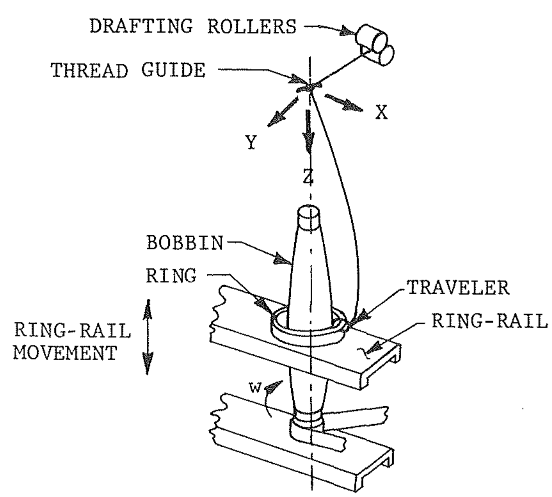

Fig. 1 Schematic Drawing of Ring-Spinning Machine

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is related to the angle of wrap, the tension of the yarn between the thread guide and the front rollers varies in a cyclic manner within each revolution of the balloon or traveler. Thus, a peak tension occurs during a revolution of the traveler and this peak may be considerably greater than the average tension. Yarn breakage is very much related to peak tension. The peak tension within a revolution of the traveler has not been adequately studied, probably because of the limited availability of tension transducers with sufficient dynamic response to make measurements of peak tension. In commercial yarn production traveler rotational speeds typically exceed 10,000 r.p.m. One notably valuable experimental work studying peak tensions is by Graham and Bragg [1][2] who showed that peak tensions may vary considerably during spinning even though the average tension is held constant.

In addition to the angle of wrap about the thread guide, there are many parameters which influence both the peak yarn tension and average tension. A few significant factors are spindle speed, balloon height, bobbin fullness, traveler weight, yarn weight, and others. The research described in the following paragraphs was planned to analyze how these and other factors influence peak tension and to develop a procedure for calculation of peak tension and the relative relationship between peak tension and average tension during ring-spinning.

Background

A number of researchers have analytically and experimentally studied the dynamics of yarn in the balloon region during ring-spinning. One of the first major contributions was by Lindner [2] who developed a solution for the shape of the balloon utilizing several simplifying approximations. Later work by Hannah [3], Mack [4], and Crank [5] further refined the analytical solutions and showed that the solutions compared well with experimental measurements of balloon shapes. The work of these and other researchers has been consolidated and extended by Hannah [6] and DeBarr [7]. A study of the dynamics of balloon collapse was conducted by Turteltaub and Bejar [8].

Although all of these studies, and several others, are of considerable value in analyzing the dynamic characteristics of spinning balloons, an analytical solution which allows for a simplified calculation of average and peak tension in the region between the thread guide and the front rollers would be of considerable value for the analysis of peak tensions during spinning. For this purpose the analytical procedure described in the following paragraphs was developed.

Notation, Basic Equations

Throughout this paper, Latin and Greek letters respectively represent dimensional and nondimensional quantities. We are initially interested in the computation of the yarn tension q at the thread guide as well as the tensions q_E, q_T and q_B below the thread guide, above the traveler and at the bobbin respectively. We consider known data the geometry of the spinning frame (see Fig. 2) defined by the angle β between the horizontal and the piece of yarn going from the front rollers to the thread guide, the distance h between the thread guide and the ring, the ring-radius r and the angle δ between the piece of

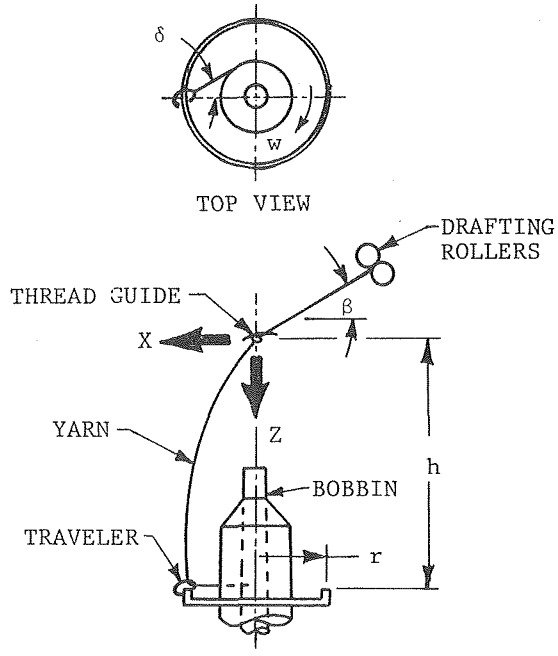

Fig. 2 Definition of Geometric Parameters for a Typical Ring Spinning Machine

yarn going from the traveler to the bobbin and a horizontal line joining the traveler and the center of the bobbin. Also known data are the mass per unit length of yarn m_Y, the mass of the traveler m_T, the coefficients of friction η_Y between yarn and metal and η_T between traveler and ring and the angular velocity w of the traveler. This angular velocity is equal to the angular velocity of the bobbin minus the quotient between delivery speed of the front rollers and ring-radius. The list of data is completed with definition of the angle ϵ that the traveler has rotated around the ring and which is measured from its back-most position. Briefly, our problem consists in the determination of q, q_E, q_T, and q_B as functions of the variable ϵ and of the dimensional data β, h, r, δ, η_Y, η_T, w, m_Y, and m_T.

It is convenient to group these variables and parameters to determine the nondimensional variables

$$\mu = hw\sqrt{m_Y/q_E} \tag{1}$$

and

$$\begin{aligned} \theta_1 &= q_E/q \\ \theta_2 &= q_T/q_E \\ \theta_3 &= q_B/q_T \end{aligned} \tag{2}$$

Although these unknowns are functions of ten variables, it will become apparent later that a certain reduction can be obtained in the size of the problem. Indeed, several of the dimensional data, may be ex-

[2] Numbers in brackets designate References at end of paper.

Nomenclature

q = yarn tension between thread guide and front rollers
q_E = yarn tension below thread guide
q_T = yarn tension above traveler
q_B = yarn tension at bobbin or below traveler
β = angle of yarn between front rollers and thread guide with horizontal
h = distance from thread guide to ring
r = ring radius
δ = angle between yarn from traveler to bobbin and centerline from traveler to bobbin centerline
m_Y = yarn mass per unit length
m_T = traveler mass
w = angular velocity of the traveler and balloon
η_Y = coefficient of friction between yarn and metal thread guide or traveler
η_T = coefficient of friction between traveler and ring
ϵ = angular position of the traveler measured from backmost position on ring
ϕ_E, ϕ_T = angle of wrap of yarn about thread guide and traveler
ψ_E, ψ_T = angle between tangents to yarn approaching and leaving the thread guide and traveler
τ_x^E, τ_y^E, τ_z^E = components of unit tangent of yarn below thread guide
τ_x^T, τ_y^T, τ_z^T = components of unit tangent of yarn above traveler

pressed by the two parameters

$$\gamma = h/r$$
$$\lambda = m_T r/m_Y h^2 \tag{3}$$

Turning to the solution of our problem, we introduce several simplifications. First, we assume that there is Coulomb friction between the yarn and metal and also that the curves formed by the yarn being wrapped on both the thread guide and the traveler are plane, the angles of wrap being respectively ϕ_E and ϕ_T, to be evaluated briefly. Then, as a consequence of equation (2),

$$\theta_1 = \exp^{\eta_y \phi E}$$
$$\theta_3 = \exp^{\eta_y \phi T} \tag{4}$$

If ψ_E and ψ_T are the angles between the tangents to the yarn at the thread guide and traveler respectively, then

$$\phi_E = \pi - \psi_E$$
$$\phi_T = \pi - \psi_T$$

Next, we employ the relation

$$\theta_2 = 1 - \mu^2/2\gamma^2 \tag{5}$$

which, as shown by Mack [4], is correct if the shape of the balloon formed by the rotating yarn does not change with time and the air drag is normal to the yarn.

To continue building our model, it is convenient to introduce a cartesian coordinate system with origin at the thread guide, Z-axis pointing downward along the spindle and rotating with angular velocity, w, in such a manner that the traveler is always on the X-Z plane. We call τ_x^E, τ_y^E, τ_z^E the components of the unit tangent to the yarn at the lower side of the thread guide. Similarly, τ_x^T, τ_y^T, τ_z^T are the components of the tangent above the traveler. With this notation, we note that

$$\cos \psi_E = + \tau_x^E \cos \epsilon \cos \beta - \tau_y^E \sin \epsilon \cos \beta \tag{6}$$

and

$$\cos \psi_T = -\tau_x^T \cos \delta + \tau_y^T \sin \delta. \tag{7}$$

The first of these relations which defines ψ_E, the compliment of the angle of wrap around the thread guide, is obtained computing the scalar product of the unit tangent vectors to the yarn above and below the thread guide, with an analogous technique being used for the angle of wrap about the traveler.

Next, we assume that the only forces acting on the traveler are a centrifugal force $m_T w^2 r$, the yarn tensions q_T, q_B, and a reaction of the ring with components f_x, f_y, f_z that satisfy Coulomb's friction law

$$f_y^2 = \eta_T^2 (f_x^2 + f_z^2) \tag{8}$$

In view of these hypotheses, the equations of equilibrium of the traveler are

$$f_x - q_T \tau_x^T + q_B \cos \delta - m_T w^2 r = 0$$
$$f_y - q_T \tau_y^T - q_B \sin \delta = 0$$
$$f_z - q_T \tau_z^T = 0$$

Substituting these into equation (8) and using equations (1), (2), and (3) yields

$$(\tau_y^T + \theta_3 \sin \delta)^2 = \eta_T^2 \left\{ \left(\lambda \frac{\mu^2}{\theta_2} + \tau_x^T - \theta_3 \cos \delta \right)^2 + (\tau_z^T)^2 \right\} \tag{9}$$

We now need estimates of the tangent vector to the yarn. Such estimates require a study of the shape of the balloon formed by the rotating yarn. This is a complex problem which has been the subject of numerous investigations carried out, among others, by Lindner [2], Mack [4], Capello [9], and DeBarr [7]. Here we use results obtained by Turteltaub and Bejar [8]. As shown in reference [8], if air drag is neglected, then the vertical component of the tension is a constant here called a, so that

$$q_E \tau_z^E = q_T \tau_z^T = a \tag{10}$$

Further, if we define a nondimensional parameter, α,

$$\alpha = \frac{hw}{a} \sqrt{m_Y q_E} \tag{11}$$

then Turteltaub and Bejar [8] have shown

$$\tau_x^E = \frac{\mu}{\gamma \sin \alpha}$$
$$\tau_y^E = 0$$
$$\tau_z^E = \frac{\mu}{\alpha} \tag{12}$$

From equation (12), since the tangent vector of the yarn is of unit magnitude it follows, after an elementary calculation, using the relationship $(\tau_x)^2 + (\tau_y)^2 + (\tau_z)^2 = 1$, we infer

$$\frac{\mu^2}{\alpha^2} + \frac{\mu^2}{\gamma^2 \sin^2 \alpha} = 1 \tag{13}$$

Also, since in the absence of air drag the curve is plane, i.e., $\tau_y^T = 0$, and since the tangent vector to the yarn is of unit magnitude, it follows from equations (1), (5), (10), and (12) that

$$\tau_x^T = \sqrt{1 - \left(\frac{\mu}{\alpha\theta_2}\right)^2}$$
$$\tau_y^T = 0$$
$$\tau_z^T = \frac{\mu}{\alpha\theta_2} \tag{14}$$

The vanishing of the Y-component of the tangent vectors transforms equations (6), (7), and (9) into the simpler formulae

$$\cos \psi_E = + \tau_x^E \cos \epsilon \cos \beta - \tau_z^E \sin \beta \tag{15}$$

$$\cos \psi_T = -\tau_x^T \cos \delta \tag{16}$$

and

$$\mu^2 = \frac{\theta_2}{\lambda} \left\{ -\tau_x^T + \theta_3 \cos \delta - \sqrt{\left(\frac{\theta_3 \sin \delta}{\eta_T}\right)^2 - (\tau_z^T)^2} \right\} \tag{17}$$

Calculation of Yarn Tension

The previous equations may be used to compute the yarn tension provided the measurable physical characteristics of the yarn and spinning frame are known. The parameters h, r, β, δ, w, m_T, m_Y, η_T, and η_y are assumed known from physical measurement and constant for a particular spinning condition. Values of interest for ϵ, the angular position of the traveler, are selected. Nondimensional parameters γ and λ are computed using equation (3). A value for α is selected such that $0 < \alpha < 3.14$. An initial value of μ is computed using equation (13) or alternately using the graph presented by Turteltaub and Bejar [8]. Next, θ_2 is computed using equation (5), τ_x^T and τ_z^T using equation (14), ψ_T using equation (16), θ_3 using equation (4), and μ recomputed using equation (17). The new value of μ is compared to the value computed based on the assumed value for α and if they compare the calculation continues. If they do not compare a new value of α is selected and the above calculation procedure repeated. It has been found that satisfactory convergence of μ is generally obtained within less than five iterations and usually two or three iterations. Next, calculate τ_x^E and τ_z^E using equation (12), ψ_E using equation (15), θ_1 using equation (4), q_E using equation (1), and q using equation (2). This completes the calculation procedure for the selected physical parameters. The procedure can be repeated to determine yarn tension at other conditions such as different angular position of the traveler on the ring or different balloon height, etc.

If one of the physical parameters such as traveler mass or spindle speed is left undetermined, the iteration procedure is not required and the value of this parameter is directly determined from calculation using the assumed value of α (or μ) and the yarn tension for the computed value of the parameter determined by continuation of the procedure outlined above.

It is possible to specify physical parameters for which there is no value of α between 0 and 3.14 which will provide convergence in the calculation of μ. This indicates that the physical parameters have been selected such that the yarn balloon is unstable for these conditions as discussed by Turteltaub and Bejar [8] and different physical parameters must be selected to obtain a solution with practical value.

Comparison with Experimental Results

In order to study the tension variation within a single cycle of the traveler, a special tension transducer was constructed. The transducer measures variations in yarn tension by measuring small forces applied to a quartz crystal positioned against the yarn in the region between the thread guide and the front roll. The transducer exhibited a dynamic response in excess of 10,000 hertz. The variation in tension measured by this transducer was recorded by photographing the trace of an oscilloscope connected to the output of the transducer. Another lower frequency transducer was used to measure the average tension, averaged over several cycles of the traveler.

Measurements of yarn tension were made on a Saco-Lowell Duo-Roth spinning frame located in the pilot spinning laboratories of USDA-ARS at Clemson, South Carolina. The conditions of measurement were: yarn size—30's cotton count with a linear density, m_Y, of 0.1970×10^{-4} kg/m; ring diameter—2.0 in. or ring radius, r, of 0.0254 m; the ring rail halfway up the bobbin resulting in a balloon height, h, of 0.272 m; the angle β of the yarn above the thread guide 59 deg, the bobbin half full of yarn such that δ equals 45 deg; the traveler rotational speed, w, of 11,000 rpm or 1151.9 radians per second; and the traveler mass, m_T, 0.648×10^{-4} kilograms. The coefficient of friction of the yarn to metal thread guide or traveler, η_Y, was chosen to be 0.300 and of the traveler to ring, η_T, to be 0.094 using data on friction coefficients published by Howell, Mineszkis, and Tabor [10].

The experimentally measured yarn tension and the value of yarn tension predicted by the analytical procedure are both plotted in Fig. 3. The agreement is very good. Both indicate a tension variation of approximately plus or minus 0.02 N. The peak in the experimental curve lags slightly behind that of the analytical curve. This is expected as the analytical curve does not consider air drag on the yarn in the balloon region and therefore the balloon is considered to be laying in a vertical plane above the traveler. In the actual case, measured experimentally, air drag on the yarn causes the yarn at the top of the balloon to lag behind the traveler.

The analytical procedure was compared with experiment only for this one case where experimental data were available. The good comparison may be somewhat fortuitous and the precision of the results of this analytical procedure needs to be further studied. However, the application of the procedure to yield results was extremely simple, requiring only seconds on a computer, and easily calculatable by hand using a hand calculator. Such a simple calculation procedure for approximating yarn tension may be of considerable value.

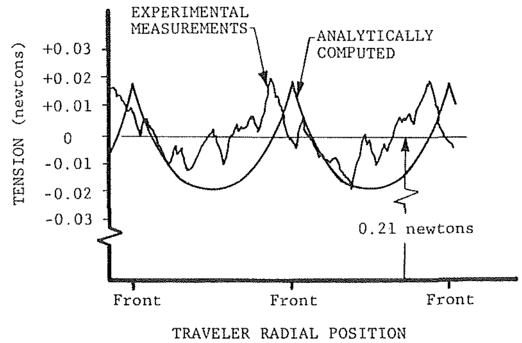

Fig. 3 Variation in Tension with Traveler Radial Position

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