Dynamic Measurement of Interfilament Friction on Staple Yarns

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Synopsis

A new method is presented which permits the quantitative characterization of interfilament friction of staple yarns using loss tangent tanδ data measured directly from samples nondestructively with the Rheovibron DDV-II viscoelastometer. The procedure is derived from a phenomenological model of the structure's mechanical behavior in which its energy dissipation capacity consists of both filament internal viscous friction and a filament-to-filament coulomb friction mechanism. By treating the coulomb dissipation in terms of an additional effective viscous component, the loss tangent of the model representing the structure can be analytically expressed in terms of the internal filament viscous properties, a fiber-to-fiber coulomb parameter, and an undetermined assembly dispersion factor which is representative of strength. By measuring effective loss tangent data for the staple yarn and a constituent filament at two separate frequencies and considering the magnitude of the coulomb mechanism to be independent of the test frequency in the range employed, both the coulomb friction dissipation and the assembly dispersion factor can be quantified. Using this procedure, loss tangent data from tests on a series of staple yarns (nylon, polyester, and acrylic fiber) are used to calculate both assembly dispersion and interfilament coulomb friction factors.

INTRODUCTION

Frictional effects play a major role in the dynamic response of yarns, webs, and fabrics. However, two types of friction must be considered.[1] First, there is internal polymer friction. The response of polymers to small sinusoidal deformations has received considerable attention through the years, generally within the framework of viscoelasticity and structure–properties relationships.[2,3] Energy losses in the dynamic deformation of webs of staple fibers must be interpreted in terms of interfilament friction.[4] However, dynamic deformations of continuous filament twisted yarns would possess both *intrafilament* and *interfilament* contributions. This problem has been considered in a study of the propagation of strain waves in continuous filament yarns.[5–7]

In this paper a new method for investigating interfilament friction of staple yarns is presented and the effects of frictions on nylon, polyester, and acrylic staple yarns are shown.

ANALYTICAL DEVELOPMENT

A sinusoidal tensile strain is imposed on fiber, thus producing a sinusoidal tensile stress. The instrument uses two transducers to read directly the absolute dynamic modulus $|E^*|$ (the ratio of maximum stress amplitude to maximum strain amplitude) and the phase angle δ between stress and strain. From these two quantities the real part E' and imaginary part E'' of the complex dynamic tensile modulus E^* can be calculated by the following relationships:

$$E' = |E^*| \cos\delta \qquad (1)$$

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$$E'' = |\bar{E}^*| \sin\delta \tag{2}$$

$$E''/E' = \tan\delta \tag{3}$$

The phase angle $\tan\delta$ is the mechanical damping (internal friction) that gives the amount of energy dissipated as heat during the periodic deformation of the fiber. The phase angle $\tan\delta$ is read directly on the Vibron instrument by using this principle.[8]

In order to extend the dynamic mechanical analysis to staple yarn, the useful model representing a staple yarn structure consists of three lumped mechanical elements used as illustrated in Fig. 1. These elements are (a) a linear elastic spring K which stores energy; (b) an energy dissipation mechanism associated with the internal viscosity η of the filaments; and (c) an energy dissipation mechanism of the coulomb form associated with filament-to-filament surface friction f. In this model, coulomb friction (constant frictional force whose direction always opposes the rate of displacement) immensely complicates the analysis because of its nonlinear character. Therefore, an attempt is made to replace it with an "equivalent viscosity." This means an addition to the viscosity η which dissipates identical energy as the coulomb dissipation, f.

The mathematical analysis of this system is as follows: When a sinusoidal displacement is applied to the sample, then

$$X = A \sin\omega t \tag{4}$$

where X = displacement, A = amplitude, ω = frequency of vibration, and t = time. The energy dissipation per cycle due to coulomb friction (ϵ_f) is

$$\epsilon_f = 4 \int_0^{\pi/2} f \frac{dx}{d(\omega t)} d(\omega t) = 4fA \int_0^{\pi/2} \cos\omega t d(\omega t) = 4Af \tag{5}$$

Similarly, energy dissipation per cycle due to internal friction (ϵ_η) is

$$\epsilon_\eta = \int \eta \frac{dx}{dt} dx = \int \eta \left(\frac{dx}{dt}\right)^2 dt = \eta A^2\omega \int \cos^2 \omega t d(\omega t) = \eta A^2\omega \tag{6}$$

Equivalent viscous dissipation is obtained by equating (5) and (6):

$$\eta_{eq} = \frac{4f}{A\omega} \tag{7}$$

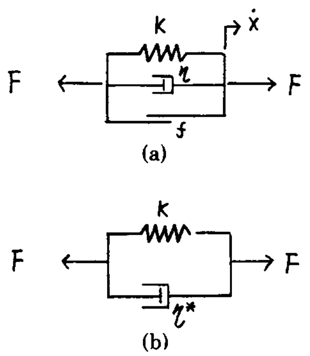

Fig. 1. Mechanical model of the staple yarn structure.

TABLE I
Loss Tangent tan δ_s of Staple Yarns[a]

Staple Yarn Sample No.	$\tan\delta_s$ 3.5 Hz	11 Hz	35 Hz	110 Hz
Nylon A-1	0.052	0.048	0.047	0.043
Fiber in A	0.032	0.028	0.024	0.020
PET B-1	0.040	0.037	0.035	0.033
Fiber in B	0.024	0.020	0.017	0.014
Acrylic C-1	0.071	0.067	0.066	0.062
Fiber in C	0.052	0.048	0.044	0.040

[a] Measured at 0% R.H., 22°C; values average 10 tests.

Thus, we may approximate the mechanical behavior of the sample by a two-element model of which "effective" viscosity is given by [see from Fig. 1(a) to Fig. 1(b)]

$$\eta^* = \eta = 4f/A\omega \tag{8}$$

The force output F is

$$F = KX + \eta^* \frac{dx}{dt}$$

Substituting $X = A \sin\omega t$ and rearranging, we obtain

$$F = \frac{KA}{\cos\delta} \sin(\omega t + \delta) \tag{9}$$

where

$$\tan\delta = \eta^*\omega/K \tag{10}$$

Therefore, the tangent of the phase angle (as directly read from Vibron) is the ratio of energy dissipation to energy storage. Loss tangent $\tan\delta$ may prove itself to be a very useful parameter in characterizing the staple yarn. However, in order to quantify the internal, filament-to-filament friction and the assembly factor separately, the expressions were expanded by using $\tan\delta$ measurements taken at two separate frequencies.[9]

The effective loss tangent for a staple yarn measured on the Vibron at a specific frequency ω_1 can be written in form

$$\tan\delta \Big|_{\omega_1}^{sy} = C \frac{\eta_f \omega_1}{K} \Big|_{\omega_1} + \frac{4f}{AK} \tag{11}$$

where C is the assembly dispersion factor which should be related to staple geometry and strength of yarn and/or degree of bulkiness, η_f is the viscosity which is an energy dissipation mechanism due to the internal friction of the filaments.

The quantity $4f/AK$ is very simply related to the interfilament friction (filament-to-filament friction). The interfilament friction ($f_s = 4f/AK$) can be expressed by the following equation:

$$f_s = \tan\delta \Big|_{\omega_1}^{sy} - C \tan\delta \Big|_{\omega_1}^{fil} \tag{12}$$

TABLE II
Interfilament Friction f_s and Assembly Dispersion Factor C of Staple Yarns

	C			f_s		
	11–110 Hz	3.5–35 Hz	3.5–110 Hz	11–110 Hz	3.5–35 Hz	3.5–110 Hz
Nylon A-1	0.625	0.75	0.75	0.0305	0.032	0.028
PET B-1	0.666	0.714	0.70	0.0238	0.0230	0.0232
Acrylic C-1	0.625	0.625	0.715	0.037	0.0385	0.038

The factor C can be determined quantitatively by measuring the loss tangent of fiber and yarn at two frequencies.[9] The interfilament friction of staple yarn can be measured directly on the Vibron using staple yarn and constituent fiber samples.

TEST PROGRAM AND RESULTS

A series of loss tangent measurements was made on three samples of the experimental staple yarns (nylon 66, polyester, and acrylic fiber) using the Rheovibron DDV-II. These yarns were drafted from 8–10 staple fibers. The size of the staple yarns was 80–100 mg/meter. The dynamic tests were conducted at four specific frequencies (3.5, 11, 35, and 110 Hz) and at 22°C, 0% R.H. Equation (12) is used to quantitatively compute the interfilament friction factor for all combinations of frequency with a ratio of 10 or greater.

Table I shows the loss tangent data of the three different staple yarns and constituent spun fibers at four frequencies. The loss tangents of the staple yarns were higher than those of constituent fibers. This additional energy dissipation of yarn is caused by the fiber-to-fiber friction (internal friction of the yarn). The results of the interfilament friction factor f_s and the assembly dispersion factor C are summarized in Table II. A total of ten tests on five samples of each material was made. No significant variation in results was observed. The small variation of both the factors f_s and C irrespective of the test frequency represents further justification of their independence of test frequency and their true representation of geometric characteristics of the staple structure as it relates to filament surface interaction.

In this experiment the friction f_s is the mean value of friction of the staple yarn test specimens which include local friction of yarn elements caused by the local velocity and pressure on filaments.

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