Open forum

EFFECT OF TEMPERATURE ON NON-LINEAR DYNAMICAL PROPERTY OF STUFFER BOX CRIMPING AND BUBBLE ELECTROSPINNING

by

Jian-Xin HUANG [a], Hai-Feng LI [d], Min-Feng SONG [a], Rou-Xi CHEN [c,d], Ping WANG [c,d,*], and Ji-Huan HE [c,d*]

[a] Nantong Cellulose Fibers Co. Ltd, Nantong, China
[b] China Tobacco Zhenjiang Industrial Co. Ltd., Zhenjiang, China
[c] National Engineering Laboratory for Modern Silk, College of Textile and Engineering, Soochow University, Suzhou, China
[d] Nantong Textile Institute, Soochow University, Nantong, China

Short paper
DOI: 10.2298/TSCI130203041H

The velocity of axially moving slender fiber of viscoelastic fluid is an important factor in mass-production of crimped fibers in stuffer box crimping and bubble electrospinning. A governing equation for fiber crimp is obtained by the Hamilton's principle, and the natural frequency and critical axially moving velocity are obtained analytically by considering the thermal effect. It is concluded that a high temperature gradient can greatly enhance the production ratio and guarantee the fundamental transverse vibration. Additionally the effects of the tensile axial load and amplitude on transverse vibration are also elucidated.

Key words: *axially moving fiber, natural frequency, mode shape, variational principle, crimped fiber*

Introduction

Crimped fibers, especially crimped nanofibers, have many potential applications in air filtration, water filtration, radiation protection, fuel cell, and many others due to high surface-to-volume ratio. The stuffer box crimping [1] (fig. 1) is widely used for fabrication of crimped fibers with diameters larger than 1 micrometer (fig. 2), and the bubble electrospinning [2, 3] (fig. 3) is used for production of crimped nanofibers with diameters less than 1000 nanometers (fig. 4) [4, 5].

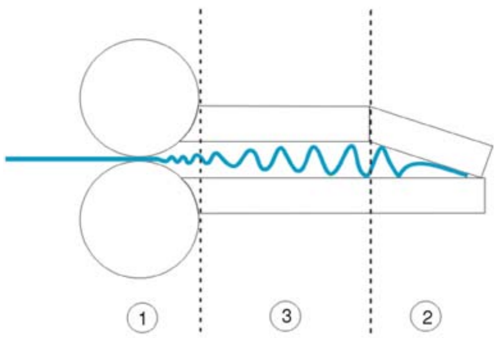

Figure 1. Crimping mechanism in the stuffer box

* Corresponding authors; e-mail: hejihuan@suda.edu.cn, pingwang@suda.edu.cn

Figure 2. Morphology of crimped fibers

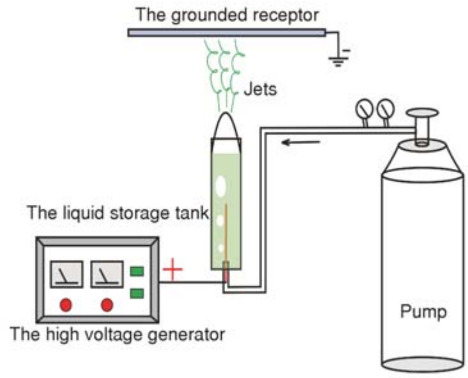

Figure 3. Crimping mechanism in the bubble electrospinning

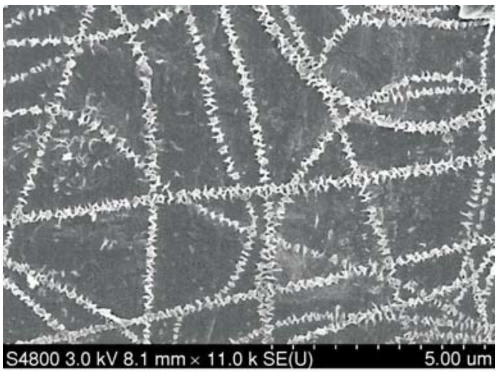

Figure 4. Morphology of PLA/DMF crimped nanofibers by bubble electrospinning

The mechanism of fiber crimp is due to the transverse vibration of an axially moving slender fiber of viscoelastic fluid before solidification, in this paper we will study the thermal effect on transverse vibration.

Governing equation

In this paper we will use the Hamilton's principle to derive the governing [6]:

$$\int_0^L (\delta K - \delta U)\mathrm{d}x = 0 \tag{1}$$

where K is the kinetic energy of the moving fiber, U – the total potential energy, and L – the length of the fiber.

The kinetic energy of the moving fiber can be written in the form [7]:

$$K = \frac{1}{2}\rho A\int_0^L \left(\frac{\mathrm{D}w}{\mathrm{D}t}\right)^2 \mathrm{d}x \tag{2}$$

where w is the transverse displacement, A section area, Dw/Dt material derivative of the transverse displacement, defined as:

$$\frac{\mathrm{D}w}{\mathrm{D}t} = \frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} \tag{3}$$

where u is the velocity of the moving fiber. Equation (2) can be written in an equivalent form:

$$K = \frac{1}{2}\rho A\int_0^L \left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x}\right)^2 \mathrm{d}x \tag{4}$$

The potential energy constitutes the following three parts.

(1) Work done by the compressive and tensile axial loads:

$$U_1 = \int_0^L N\varepsilon_{\mathrm{L}} \mathrm{d}x \tag{5}$$

where N can be expressed as:

$$N = FA - PA \tag{6}$$

where F is the liquid fiber's tension per area and P – the fluid pressure. According to Bernoulli equation, the fluid pressure can be approximately written in the form:

$$P(x) = \rho B - \frac{1}{2}\rho u^2 \tag{7}$$

The non-linear strain reads [8] :

$$\varepsilon_{\mathrm{L}} = \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \alpha \Delta T \tag{8}$$

where α is a constant and ΔT – the temperature gradient.

(2) Potential energy

$$U_2 = \int_0^L \frac{1}{2} EA(\varepsilon_{\mathrm{L}})^2 \mathrm{d}x \tag{9}$$

(3) Bending energy

$$U_3 = \int_0^L \frac{1}{2} EI\left(\frac{\partial^2 w}{\partial x^2}\right)^2 \mathrm{d}x \tag{10}$$

The total potential energy for the moving fiber is:

$$U = \int_0^L \left[N\varepsilon_L + \frac{1}{2}EA(\varepsilon_L)^2 + \frac{1}{2}EI\left(\frac{\partial^2 w}{\partial x^2}\right)^2 \right] \mathrm{d}x \tag{11}$$

or

$$U = \int_0^L \left\{ N\left[\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \alpha\Delta T\right] + \frac{1}{2}EA\left[\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \alpha\Delta T\right]^2 + \frac{1}{2}EI\left(\frac{\partial^2 w}{\partial x^2}\right)^2 \right\} \mathrm{d}x \tag{12}$$

Using eq. (1), and considering the following relation:

$$\delta K = \rho A \int_0^L \left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x}\right)\delta\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x}\right)\mathrm{d}x =$$

$$= \rho A \int_0^L \left(\frac{\partial w}{\partial t}\delta\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x}\delta\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial t}\delta\frac{\partial w}{\partial x} + u^2\frac{\partial w}{\partial x}\delta\frac{\partial w}{\partial x}\right)\mathrm{d}x \tag{13}$$

we can obtain the following governing equation:

$$\rho A\left(\frac{\partial^2 w}{\partial t^2} + 2u\frac{\partial^2 w}{\partial t \partial x} + u^2\frac{\partial^2 w}{\partial x^2}\right) -$$

$$-N\frac{\partial^2 w}{\partial x^2} - 2EA\frac{\partial}{\partial x}\left\{\left[\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \alpha\Delta T\right]\frac{\partial w}{\partial x}\right\} + EI\frac{\partial^4 w}{\partial x^4} = 0 \tag{14}$$

or

$$\rho A\left(\frac{\partial^2 w}{\partial t^2}+2u\frac{\partial^2 w}{\partial t\partial x}+u^2\frac{\partial^2 w}{\partial x^2}\right)-N\frac{\partial^2 w}{\partial x^2}-$$
$$-3EA\left(\frac{\partial w}{\partial x}\right)^2\frac{\partial^2 w}{\partial x^2}-2EA\alpha\Delta T\frac{\partial^2 w}{\partial x^2}+EI\frac{\partial^4 w}{\partial x^4}=0 \quad (15)$$

Critical velocity of the axially moving slender fiber

The velocity of the axially moving slender fiber plays a key role in mass-production of crimped fibers. A higher velocity is much needed for a higher production ratio, however an increase of u might result in no transverse vibration, as a result, no crimped fibers can be produced. Therefore, it is necessary to pick out the main factors affecting the critical velocity of the axially moving slender fiber.

The solution of eq. (15) can be presented in the form:

$$w(x,\ t)=W(x)\cos\omega t \quad (16)$$

where W is the normal function and ω – the natural frequency. Substituting eq. (16) into eq. (15) results in :

$$\rho A(-\omega^2 W\cos\omega t-2\omega uW'\sin\omega t+u^2W'\cos\omega t)-$$
$$-NW'\cos\omega t-3EAW^2W'\cos^3\omega t-2EA\alpha\Delta TW'\cos\omega t+EIW^{(4)}\cos\omega t=0 \quad (17)$$

Using the Galerkin technology, we obtain the following differential equation for the mode shape of vibration:

$$-\omega^2\rho AW+\rho Au^2W''-NW''-\frac{9}{4}EAW^2W''-2EA\alpha\Delta TW''+EIW^{(iv)}=0 \quad (18)$$

The expression of the normal function is assumed to have the form:

$$W=w_{\max}\sin\left(\frac{\pi}{L}x\right) \quad (19)$$

and eq. (18) becomes:

$$-\omega^2\rho Aw_{\max}\sin\left(\frac{\pi}{L}x\right)+(-\rho Au^2+N+2EA\alpha\Delta T)w_{\max}\frac{\pi^2}{L^2}\sin\left(\frac{\pi}{L}x\right)+$$
$$+\frac{9}{4}EAw_{\max}^3\sin^3\left(\frac{\pi}{L}x\right)+EIw_{\max}\frac{\pi^4}{L^4}\sin\left(\frac{\pi}{L}x\right)=0 \quad (20)$$

Using the Galerkin technology, and ignoring higher harmonic term, we have the following fundamental frequency of vibration:

$$-\omega^2\rho A+(-\rho Au^2+N+2EA\alpha\Delta T)\frac{\pi^2}{L^2}+\frac{27}{16}EAw_{\max}^2+EI\frac{\pi^4}{L^4}=0 \quad (21)$$

The fundamental frequency is:

$$\omega=\sqrt{\frac{1}{\rho A}\left[(-\rho Au^2+N+2EA\alpha\Delta T)\frac{\pi^2}{L^2}+\frac{27}{16}EAw_{\max}^2+EI\frac{\pi^2}{L^2}\right]} \quad (22)$$

Condition of stability is:

$$(-\rho Au^2+N+2EA\alpha\Delta T)\frac{\pi^2}{L^2}+\frac{27}{16}EAw_{\max}^2+EI\frac{\pi^2}{L^2}=0 \quad (23)$$

By eqs.(6) and (7), we have:

$$N = FA - \rho BA + \frac{1}{2}\rho u^2 A \tag{24}$$

and the first critical velocity:

$$u = \sqrt{\frac{2}{\rho A}\left[FA - \rho BA + 2EA\alpha\Delta T + \frac{27}{16}EAw_{\max}^2\frac{L^2}{\pi^2} + EI\frac{\pi^2}{L^2}\right]} \tag{25}$$

below which the fundamental transverse vibration occurs.

Discussion and conclusion

From eq. (25), it is obvious that a high temperature gradient can greatly improve the production ratio and guarantee the fundamental transverse for fabrication of vibration for crimped fibers. Furthermore a high temperature gradient during the spinning process can enhance solidification due to solvent evaporation. A high tensile axial load and larger amplitude of the crimped fiber are also two effective factors to improve the production ratio.

In this paper a governing equation for fiber crimp considering the thermal effect is obtained, and the first frequency and first critical velocity of the moving fiber are obtained analytically, which can be used for controlling the spinning process.

Acknowledgments

The work is supported by Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), National Natural Science Foundation of China under grant No. 11372205 and Project for Six Kinds of Top Talents in Jiangsu Province under grant No. ZBZZ-035, Science & Technology Pillar Program of Jiangsu Province under grant No. BE2013072.

References

[1] Singh, R. K., Vohra, J. N., Study of Process Mechanics and Yarn Characteristics Using a Fabricated Stuffer-Box Crimper, *Text. Res. J., 46* (1976), 3, pp. 164-170
[2] He, J.-H., Effect on Temperature on Surface Tension of a Bubble and Hierarchical Ruptured Bubbles for Nanofiber Fabrication, *Thermal Science, 16* (2012), 1, pp. 327-330
[3] Dou, H., *et al*., Blown Bubble Spinning for Fabrication of Superfine Fibers, *Thermal Science, 16* (1976), 5, pp. 1465-1466
[4] He, J.-H., *et al*., Review of Fiber Morphology Obtained by Bubble Electrospinning and Blown Bubble Spinning, *Thermal Science, 16* (2012), 5, pp. 1263-1279
[5] Chen, R. X., *et al.*, Mechanism of Nanofiber Crimp, *Thermal Science, 17* (2013), 5, pp. 1473-1477
[6] Washizu, K., *Variational Methods in Elasticity and Plasticity*, Pergamon Press, Oxford, UK, 1982
[7] Karnovsky, I. A., Lebed, O. I., *Non-Classical Vibrations of Arches and Beams*, McGraw-Hill, New York, USA, 2004
[8] Ghayesh, M. H., Khadem, S. E., Rotary Inertia and Temperature Effects on Non-Linear Vibration, Steady-State Response and Stability of an Axially Moving Beam with Time-Dependent Velocity, *International Journal of Mechanical Sciences, 50* (2008), 3, pp. 389-404

Paper submitted: February 3, 2013
Paper revised: February 4, 2013
Paper accepted: February 4, 2013