다양한 점탄성 방사공정에서 연신공명의 간단한 안정성 판별식

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Simple indicator of draw resonance instability in spinning process with various viscoelastic fluids

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Introduction

Melt Spinning process produces thin filaments with highly oriented polymer chain and enhanced mechanical properties by uniaxially drawing molten polymer faster than extrusion velocity. Many researchers have adopted the spinning process as a basic process model for the stability and sensitivity analyses of extensional deformation processes with various viscoelastic fluids. Since the stability results of a viscoelastic spinning process were first reported by Fisher and Denn (1976), many important theoretical considerations and experimental observations on the stability and related issues in polymer extensional deformation processes such as fiber spinning, film blowing, film casting and coating processes have been steadily exploited to develop optimal strategies for the stabilization and optimization of the processes (Hatzikiriakos and Migler, 2005).

In this present study, draw resonance instability has been examined using eigenfunction data from the linear stability analysis for the spinning processes with various viscoelastic fluids. White-Metzner, Phan-Thien and Tanner, Larson and Giesekus viscoelastic models were adopted to elucidate the effect of their extensional properties on the spinning stability. It has been found that extensional viscosity of the viscoelastic fluids onto the spinline plays a key role in determining the stability and dynamics of spinning system. It has been corroborated that a simple indicator, a combination of the period of oscillation and traveling times of several kinematic waves evaluated from eigenfunction data, illustrates the general stability and bifurcation phenomena of the system.

Modeling for viscoelastic spinning flow

Among the many viscoelastic constitutive equations, White-Metzner (W-M model), Phan-Thien and Tanner (PTT model), Larson, and Giesekus models as reported by Khan and Larson (1987) were selected to analyze the draw resonance instability in isothermal spinning case. One-dimensional governing equations are employed with secondary forces (inertia, gravity, air drag, and surface tension) neglected. Including them would not change the fundamental aspects of what is reported here. The origin of flow coordinate is taken as the position of maximum extrudate swell near die exit, in order to exclude the prehistory effect inside the die. Dimensionless governing equations are as follows.

Equation of continuity: $\frac{\partial a}{\partial t}+\frac{\partial (av)}{\partial x}=0$ (1)

Equation of motion: $\frac{\partial}{\partial x}(a\tau)=0$ (2)

Constitutive Equations:

W-M model: $\left[1+\alpha_{WM}\sqrt{3}De\frac{\partial v}{\partial x}\right]\tau+De\left[\frac{\partial \tau}{\partial t}+v\frac{\partial \tau}{\partial x}-2\tau\frac{\partial v}{\partial x}\right]=\frac{\partial v}{\partial x}$ (3)

PTT model: $K\tau+De\left[\frac{\partial \tau}{\partial t}+v\frac{\partial \tau}{\partial x}-2(1-\alpha_{PTT})\tau\frac{\partial v}{\partial x}\right]=\frac{\partial v}{\partial x}$, where $K=\exp\left[2\varepsilon De\tau\right]$ (4)

Larson model: $\tau+De\left[\frac{\partial \tau}{\partial t}+v\frac{\partial \tau}{\partial x}-2\tau\frac{\partial v}{\partial x}\right]+\frac{2}{3}\alpha_L De\tau\frac{\partial v}{\partial x}+\frac{4}{3}\alpha_L De^2\tau^2\frac{\partial v}{\partial x}=\frac{\partial v}{\partial x}$ (5)

Giesekus model: $\tau+\lambda\left[\frac{\partial \tau}{\partial t}+v\frac{\partial \tau}{\partial x}-2\tau\frac{\partial v}{\partial x}\right]+2\alpha_G\tau^2 De=\frac{\partial v}{\partial x}$ (6)

Boundary conditions: $a=v=1$ at x=0 (7a)

$v=r$ at x=1 (7b)

where a denotes dimensionless spinline area, v dimensionless spinline velocity, t dimensionless time, x dimensionless spinline distance, τ dimensionless axial stress, De Deborah number, r drawdown ratio, α_{WM}, ε and α_{PTT}, α_L, α_G material parameter determining the extensional properties of above fluids.

Results and discussion

Using various constitutive equations, stability windows have been established by solving the eigenproblem of the spinning (Fig. 1). Depending on whether the fluid is extension thickening or thinning, the viscoelasticity stabilizes or destabilizes the spinning system, respectively. It is noted that UCM fluid with zero material parameter in each viscoelastic fluid and W-M fluids where α is less than $1/\sqrt{3}$ clearly exhibit the second stable region in high drawdown ratio conditions due to the unrealistic high-stress buildup.

As to the PTT fluids having non-zero ε parameter, the second stable region as in White-Metzner case does not exist in high drawdown ratio regime because material parameter ε prevents the infinite growth of tensile stress (Jung, 1999). Especially, the Larson and Giesekus models give interesting stability behaviors. As depicted in Fig. 1 (c) and (d), the neutral stability curve is increased in intermediate De region and then decreased in high De region where the material parameter is 0.05.

To elucidate the different stability behaviors of above constitutive equations, elongational properties onto the spinline are evaluated. Fig. 2 displays these elongational viscosity profiles for both extension thickening and thinning fluids. In the case of the PTT model and the W-M model (Figs. 2 (a) and (b)), extension thickening and thinning are clearly demarcated, depending on their material parameters. However, elongational viscosity of the Larson model first increases at low/intermediate extension rates and then gradually decreases at high extension rates. It is regarded that flow feature is changed from extensional thickening to extensional thinning under the constant material condition, indicating the unattainable region in the Larson model. This change directly affects the destabilization of the spinning system in the intermediate De regime. It has been found that the extensional viscosity profiles in spinline play a key role in determining the stability.

To clarify the physics of the occurrence of the bifurcation and persistence of the supercritical oscillating behavior, we have focused on kinematic waves traveling along the spinline. The three kinds of waves between the die exit and the take-up (waves of spinline throughput, maximum and minimum spinline cross-section) are used for the calculation of their traveling times. A combination of the period of oscillation and traveling times of three kinematic waves illustrates the general stability and bifurcation phenomena of the system (Lee et al, 2005). Results by nonlinear transient simulation and linear stability analysis are compared in Fig. 3. Figs. 3 (a) and (b) exhibit the results of indicator equation in PTT case. In the case of Larson model (Fig. 3 (c)), solutions of high De section cannot be obtained by contact with unattainable region. In Giesekus model, two onset points are accurately obtained as in neutral stability windows (Fig. 1 (d)). Despite the fact that the values of indicator equation by linear analysis do not coincide with those by nonlinear analysis in the unstable region, these values correctly predict onset points and demarcate the stable and unstable regions.

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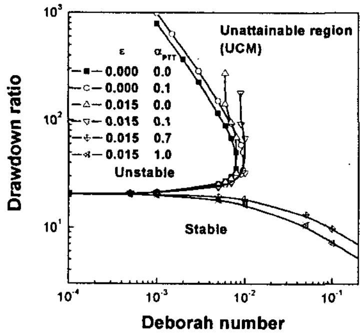
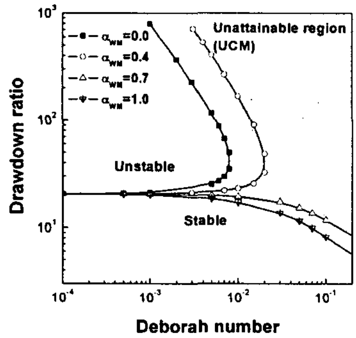
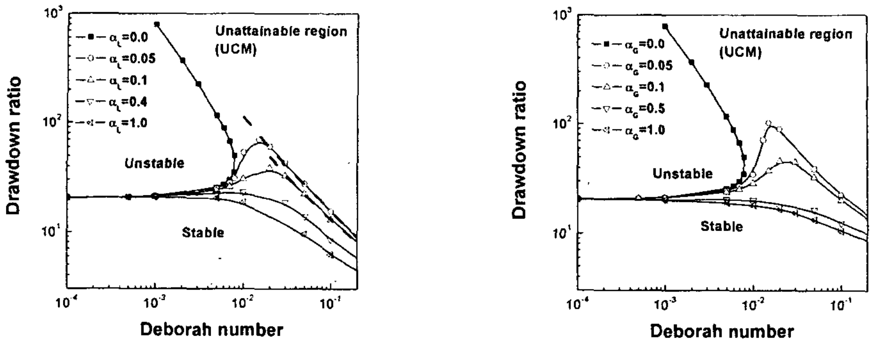


(a)



(b)



(c) (d)

Fig. 1. Stability windows: (a) PTT, (b) W-M, (c) Larson and (d) Giesekus models.

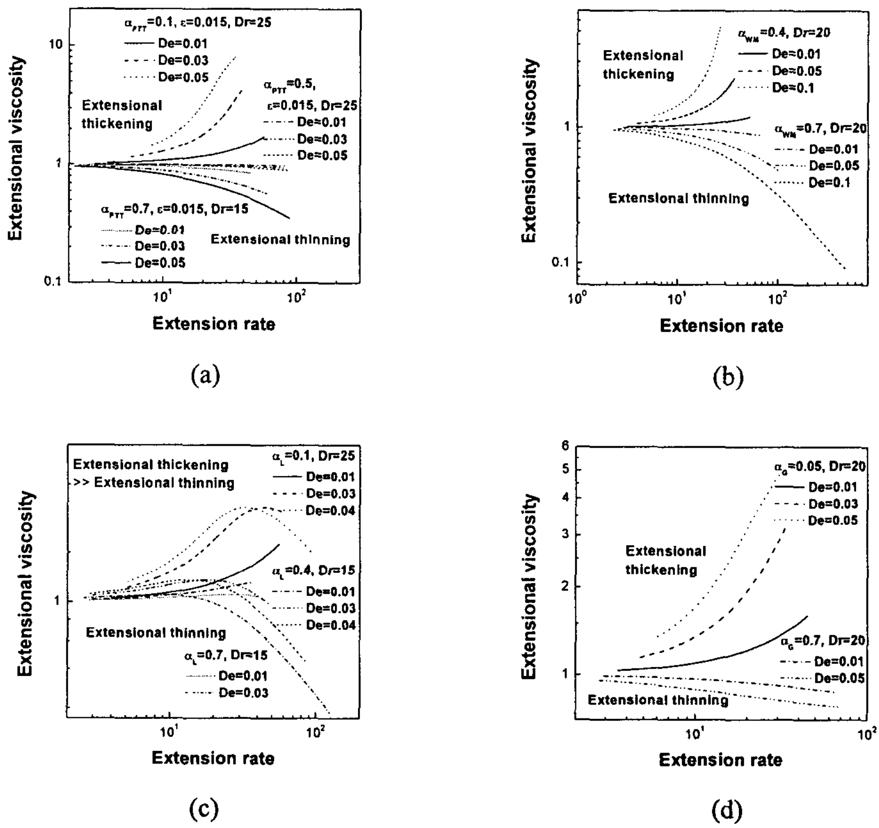


Fig. 2. Extensional viscosity: (a) PTT, (b) W-M, (c) Larson and (d) Giesekus models

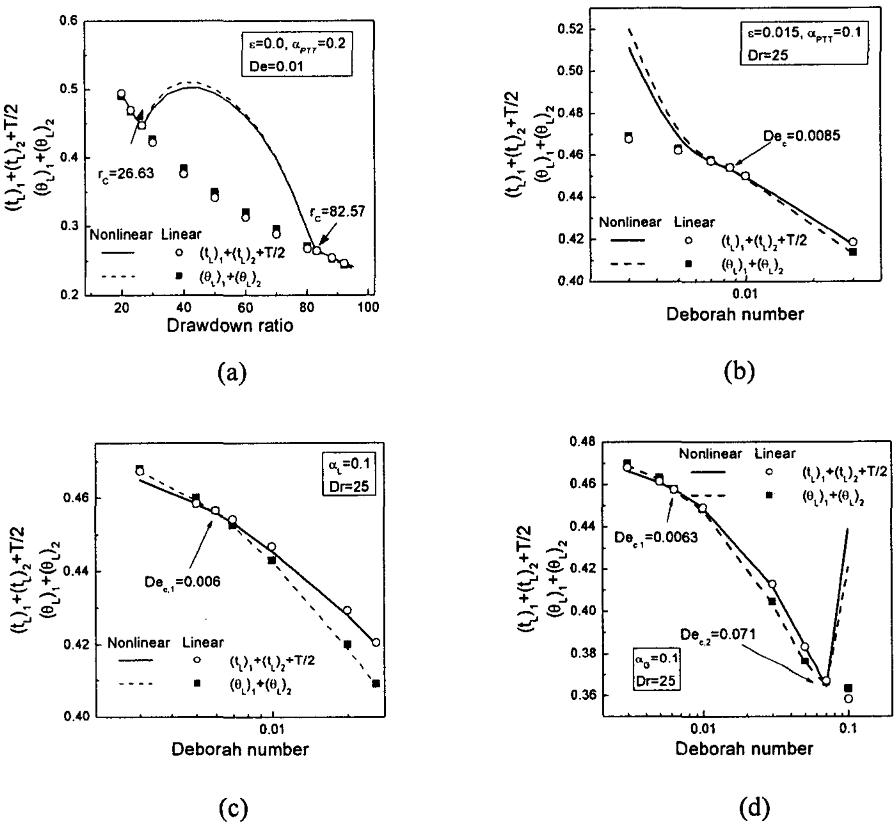


Fig. 3. Simple indicator criterion by traveling waves: (a) PTT – increasing Dr, (b) PTT, (c) Larson and (d) Giesekus models – increasing De.