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Stability windows for draw resonance instability in two-dimensional Newtonian and viscoelastic film casting processes by transient frequency response method

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ABSTRACT

Critical onsets for draw resonance instability occurring in two-dimensional (2-D) film casting processes with Newtonian and viscoelastic (Upper-Convected Maxwell and Phan-Thien and Tanner) fluids have been newly determined using a transient frequency response method. Under a constant tension condition, which guarantees always stable operation, the trajectory of a transfer function between the output take-up velocity and input tension in a Nyquist plot has been used as an indicator for finding draw resonance onsets. Various stability windows for Newtonian and viscoelastic fluids have been constructed, confirming that the onsets were well-predicted when compared with transient responses in actual velocity-controlled operating systems around the onsets. Interestingly, up-and-down stability patterns along the aspect ratio in the Newtonian cases were found to be closely related to the flow deformation features of the fluid elements within the film width. Dichotomous stability behaviors for extensional-thickening and extensional-thinning fluids were well addressed in the 2-D processes.

1. Introduction

Film casting process is one of representative extensional deformation polymer processes. In this process, highly-oriented films such as display/adhesive films, membranes, and catalytic films, can be produced by drawing a polymer melt under a relatively high draw ratio condition in the air-gap region from a slit die to a chill roll (Fig. 1). Draw ratio is defined as the ratio of the velocity at the chill roll to that at the die positions. Although the stretching operation is rather simple, inherent complicated dynamics of this process have drawn much attention in academia and industries, in terms of the viscoelasticity of polymeric liquids and nonlinear characteristics of state variables.

Considering the inevitable disturbances that affect film dynamics, there exist several defects or instabilities occurring in film casting processes – neck-in, edge-beads, and draw resonance [1]. Neck-in refers to gradually decreasing film width along the machine direction in the air-gap region. The edge-bead phenomenon with higher film thickness at both edges than at the center is closely related to neck-in [2]. Draw resonance is featured by self-sustained periodic oscillations of state variables such as film thickness, film width, and tension over a critical draw ratio. Neck-in and edge-beads are frequently observed during stable steady operation; however, draw resonance has a unique transient nature that is unavoidably encountered over unstable states.

These defects and instabilities in film casting have been theoretically and experimentally considered and reviewed by many researchers [3–5]. From simple one-dimensional (1-D) models, draw resonance onsets for Newtonian and viscoelastic fluids have been successfully determined by a linear stability method which introduces infinitesimal disturbances in nonlinear governing equations with respect to base or steady flow states [6–10]. Silagy et al. [7] developed 1-D models for Newtonian and viscoelastic Upper-Convected Maxwell (UCM) fluids with varying film width (i.e., neck-in) to analyze draw resonance. Co groups [8,9] developed two-dimensional (2-D) viscoelastic models and analyzed draw resonance under various wave number inputs from 1-D steady flows. Zavinska et al. [10] presented somewhat complicated onset curves for Giesekus fluids in 1-D nonisothermal process. Lee et al. [11,12] solved transient responses and sensitivity of 1-D models with varying film width for viscoelastic Phan-Thien and Tanner (PTT) fluids [13], reporting peculiar phase plots due to the simultaneous changes of film width and film thickness. Furthermore, Hagen group [14,15] eloquently confirmed the existence and uniqueness of steady-state solutions for 1-D Newtonian film casting process under both isothermal and nonisothermal conditions.

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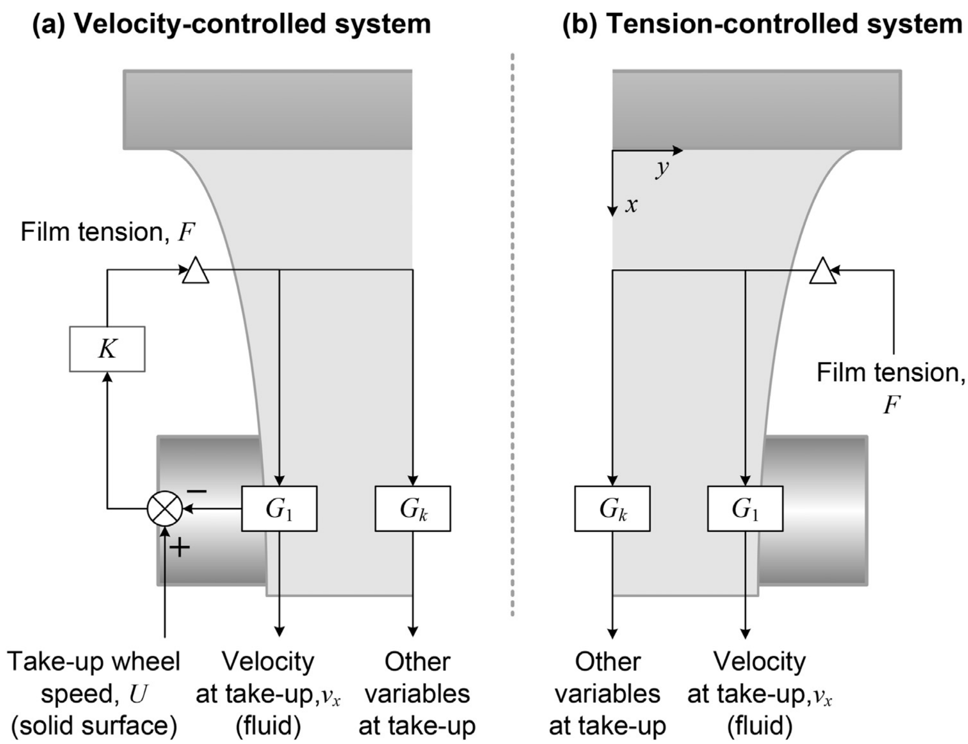

Fig. 1. Schematic diagrams for film casting system that can be operated by two modes: (a) velocity-controlled and (b) tension-controlled cases. In the conventional velocity-controlled mode, tension should be adjusted or controlled to satisfy a constant draw ratio, according to the negative feedback control loop. In the tension-controlled mode, output variables can be just solved under a constant tension condition, not inducing draw resonance instability. G_i and K are transfer function between output and input variables and proportional constant, respectively.

Higher-dimensional models need to be exploited in order to reasonably describe the variation in film width (i.e., edge-beads) as well as draw resonance and neck-in. Silagy et al. [16] roughly determined the stability at several states for 2-D Newtonian film casting around onsets by altering the ratio between the air-gap distance (L) and initial film width ($\bar{w}_0$) called the aspect ratio ($\equiv L/\bar{w}_0$), by means of direct transient simulation. They also showed steady solutions of the 2-D viscoelastic process. Kim et al. [17] and Shin et al. [18] introduced transient responses of 2-D viscoelastic processes with dichotomous extensional-thickening and -thinning behaviors. Steady film profiles by three-dimensional (3-D) models were also explained by Sakaki et al. [19] and Satoh et al. [20]. Note that the above-mentioned film dynamics were based on the actual film casting process operated under the constant draw ratio condition. As compared in Fig. 1, the process will be always stable and insensitive with respect to any disturbance, if it is controlled by a constant tension or force [21,22].

As in other extensional deformation processes, such as fiber spinning and film blowing [5,23], it is important to establish stability windows demarcating stable and unstable regions by accurately and effectively determining onsets in the film casting process. It does not appear that stability windows for higher-dimensional film casting have been constructed yet for viscoelastic fluids, due to the complexity of reformulating given nonlinear governing equations into linearized eigensystems by the linear stability method [24] and the tremendous time-consuming task of finding onsets under actual operating conditions by the direct transient simulation method. Interestingly, Kallel et al. [25] incorporated the linear stability method in the time-dependent kinematic interface equation for the 2-D Newtonian film casting process.

In this study, several representative stability windows of 2-D isothermal film casting processes for Newtonian and viscoelastic fluids (UCM and PTT fluids) were newly established. This was done by incorporating the transient frequency response method under a constant tension or force condition, which guarantees always stable states (i.e., not typical constant draw ratio), based on the previous work on the fiber spinning process [26]. Onsets were exactly determined by delineating Nyquist plots for real and imaginary parts of the transfer function between the take-up velocity (as output) and the step-changed tension (as input) perturbation under different aspect ratio, Deborah number, and material parameter conditions [27].

2. Governing equations for viscoelastic film casting flows

Dimensionless governing equations for 2-D isothermal film casting processes with viscoelastic PTT fluids were considered as follows, basically employing the same notations and schematic geometries as in previous studies [17,18].

Continuity equation:

$$\frac{\partial e}{\partial t} + \frac{\partial (e v_x)}{\partial x} + \frac{\partial (e v_y)}{\partial y} = 0, \tag{1a}$$

$$e \equiv \frac{\bar{e}}{\bar{e}_0},\ t \equiv \frac{\bar{t}\bar{v}_0}{\bar{w}_0},\ \boldsymbol{v} \equiv \frac{\bar{\boldsymbol{v}}}{\bar{v}_0} \text{ with } \boldsymbol{v} = [v_x\ v_y], \tag{1b}$$

where e denotes the dimensionless film thickness, $\boldsymbol{v}$ is the dimensionless velocity vector, t is the dimensionless time, and L is the air-gap distance from the die to chill-roll. Subscript 0 represents the die exit position (i.e., an inlet in the flow domain). Note that the overbars indicate dimensional properties.

Equations of motion:

$$\frac{\partial (e\sigma_{xx})}{\partial x} + \frac{\partial (e\sigma_{xy})}{\partial y} = 0, \tag{2a}$$

$$\frac{\partial (e\sigma_{xy})}{\partial x} + \frac{\partial (e\sigma_{yy})}{\partial y} = 0, \tag{2b}$$