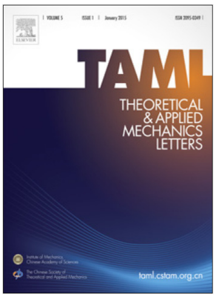

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Stability of Couette flow past a gel film

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We study instability of a Newtonian Couette flow past a gel-like film in the limit of vanishing Reynolds number. Three models are explored including one hyperelastic (neo-Hookean) solid, and two viscoelastic (Kelvin-Voigt and Zener) solids. Instead of using the conventional Lagrangian description in the solid phase for solving the displacement field, we construct equivalent "differential" models in a Eulerian reference frame, and solve for the velocity, pressure and stress in both fluid and solid phases simultaneously. We find the interfacial instability is driven by the first-normal stress difference in the base-state solution in both hyperelasic and viscoelastic models. For the neo-Hookean solid, when subjected to a shear flow, the interface exhibits a short-wave (finite-wavelength) instability when the film is thin (thick). In the Kelvin-Voigt and Zener solids where viscous effects are incorporated, instability growth is enhanced at small wavenumber but suppressed at large wavenumber, leading to a dominant finite-wavelength instability. In addition, adding surface tension effectively stabilizes the interface to sustain fluid shear.

The interaction of viscous fluid and soft objects is of considerable importance in a wide range of problems, such as rheology of complex fluids, coating, biological locomotion, and soft lubrication [1-4]. When a soft material interacts with fluid flows, the coupling between the fluid force and material elasticity can generate waves propagating at the fluid/solid interface. Understanding this behavior is critical to the study of biological swimmers and their artificial analogs as it can greatly effect the viability and efficiency of a potential swimming mode. Kumaran et al. [5] first studied the stability of an incompressible viscoelastic gel film in a Newtonian Couette flow by ignoring inertia, where a linear model is adopted to describe deformation. They found the fluid/solid interface becomes unstable when the imposed shear goes beyond a certain critical number, and the critical value of the imposed fluid shear strength varies inversely with the film thickness for sufficiently thick solids, which is verified by the following experiments by Kumaran and Muralikrishnan [6, 7]. For sufficiently thin solids, however, the linear elastic model overpredicts the critical values of the fluid shear that drives the interfacial instability. Gkanis and Kumar [8] studied the similar problem by employing a neo-Hookean solid model which admits finite/large deformation. While observing similar behaviors for thick gels, their model predicts a much smaller critical shear for thin gels, which suggests that incorporating solid nonlinearity can effectively destabilize the system. It has been identified that such interfacial instability under shear is mainly due to the first normal-stress difference appearing at the base state solutions, which is known as the Poynting effect in nonlinear solids [9, 10], and is also similar to the situation of two coupled viscoelastic liquids [11, 12]. When surface tension is incorporated into the model, it changes the short-wave instability in thin films to be finite-wavelength. Later Gkanis and Kumar [13] investigated how the flow field and combined pressure gradient impact stability of a neo-Hookean solid.

Although such elastohydrodynamic instability has been studied for simple neo-Hookean solids, in practice soft materials often exhibit more complicated constitutive behaviors than hyperelasticity. Especially for gel-like (e.g., hydrogel) materials that are typically composed of a large amount of solvent such as water and long chain polymers which can form a complex network by chemical