

Viscoelastic vortex streetUmang N. Patel , Jonathan P. Rothstein , and Yahya Modarres-Sadeghi ^{*}*Department of Mechanical and Industrial Engineering, [University of Massachusetts, Amherst](#), Massachusetts 01003, USA*

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The von Kármán vortex street is one of the most prominent and exquisite flow patterns observed in fluid dynamics. For a fluid flow past a cylinder (and other bluff bodies), flow separation and eventually alternating vortex shedding are observed in the wake at large Reynolds numbers where fluid inertia dominates the flow. It is well known that the critical Reynolds number to observe such vortex shedding in the wake of a fixed cylinder is $Re_{cr} = 47$ [1]. However, vortex shedding has been observed at values as low as $Re = 19$ for flexible or flexibly mounted cylinders [2–4]. The shedding of vortices in the wake results in a fluctuating lift force as well as a fluctuating drag force on the cylinder. If the cylinder is flexible or flexibly mounted, then these fluctuating lift forces can cause structural oscillations when the vortex shedding frequency matches the natural frequency of the system. These oscillations can be detrimental to structures such as underwater cables and pipes because they can result in fatigue and eventually lead to structural failure.

The coupling between vortex shedding and structural oscillations is called Vortex-Induced Vibrations (VIV), which is a canonical problem in Fluid-Structure Interactions (FSI) [5]. Such FSI problems have been studied extensively for Newtonian fluids at high Reynolds numbers [6–8]. In recent years, there have been a series of studies on FSI in a very different flow regime where fluid inertia is negligible and the flow is dominated by fluid elasticity: at infinitesimal Re numbers and high Wi numbers (Weissenberg number, Wi , represents the ratio of elastic forces to viscous forces). In this regime, purely elastic flow instabilities can lead to structural oscillations. These studies were conducted both experimentally and numerically by investigating the flow of polymeric (viscoelastic) fluids past flexible or flexibly mounted structures [9,10].

The relative importance of elasticity in a viscoelastic flow is described by the Weissenberg number, which can be written as the relaxation time of the fluid multiplied by the shear rate of the flow, $Wi = \lambda \dot{\gamma}$. If the shear rate is small, $Wi \ll 1$, then the viscoelastic fluid has ample time to relax back to equilibrium, and it will behave similar to a Newtonian fluid. If the shear rate is large, $Wi \gg 1$, then the viscoelastic fluid will behave like an elastic Hookean solid. The behavior of the viscoelastic fluid between these two extremes is quite rich. For an inertial-viscoelastic fluid, where $Re \gg 1$ and $Wi \gg 1$, the effects of fluid inertia and fluid elasticity are in direct competition with

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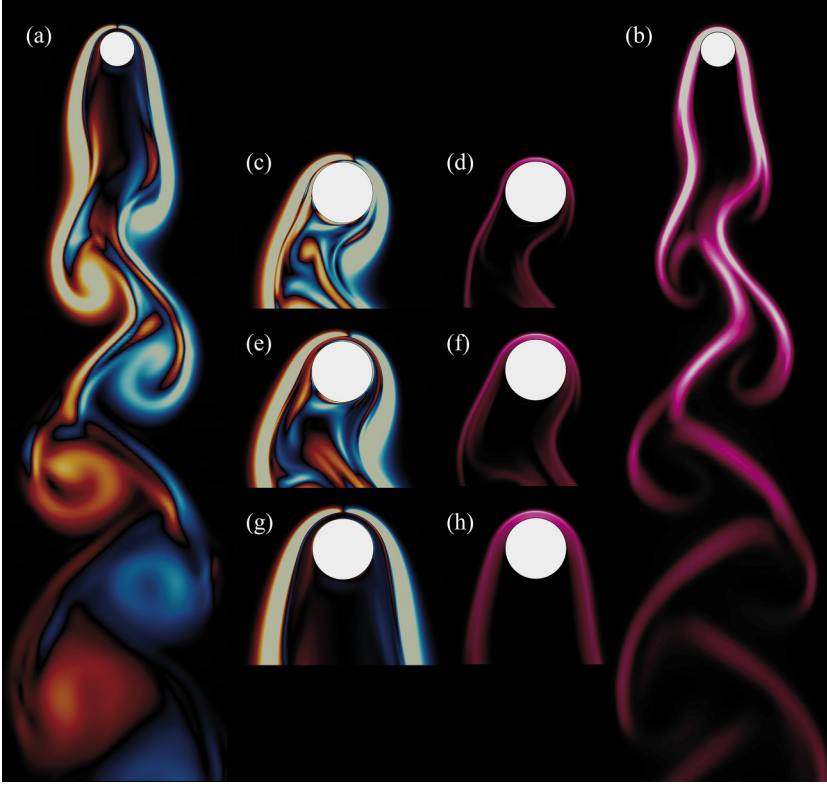


FIG. 1. Viscoelastic vortex street presented by plotting the contours of (a) normalized vorticity, $\omega_z D/U$, and (b) normalized polymeric stress, $||\tau_p||/(\eta_p/\lambda)$, for $Wi = 10$, $Re = 100$, $U^* = 5$, $\beta = 0.5$, and $L^2 = 20\,000$. The close-up contours of vorticity and polymeric stress are shown in subplots (c),(d) for $L^2 = 1\,000$, (e),(f) for $L^2 = 5\,000$, and (g),(h) for $L^2 = 20\,000$. The normalized vorticity range is -2.5 – 2.5 . The normalized polymeric stress range is 0 – $2\,000$ for subplot (b). For the close-up contours of normalized polymeric stress (d),(f),(h), the range is 0 – $12\,000$.

each other. For example, while fluid inertia can lead to flow separation *downstream* from an obstacle [11], fluid elasticity can lead to flow separation *upstream* of an obstacle [12,13] and the reduction in strength and eventual suppression of vortex formation downstream from the obstacle [14–16] can lead to the elimination of VIV [16,17].

Here we focus on the influence of fluid elasticity on the wake of a flexibly mounted cylinder undergoing crossflow VIV, by considering a system at a Reynolds number of $Re = 100$ and a Weissenberg number of $Wi = 10$, where the effects of elasticity and inertia are competitive in nature. We perform high-fidelity computational fluid dynamics (CFD) simulations of this system by solving the incompressible Navier-Stokes equations coupled with the FENE-P constitutive equations to model the fluid viscoelasticity. The simulations are performed at a reduced velocity of $U^* = U_\infty/(f_n D) = 5$ and a viscosity ratio of $\beta = \eta_p/(\eta_s + \eta_p) = 0.5$, where U_∞ is the free stream velocity, f_n is the natural frequency of the flexibly mounted cylinder, D is the cylinder diameter, η_p is the polymer contribution to the viscosity, and η_s is the solvent contribution to the viscosity.

The normalized vorticity, $\omega_z D/U$, is shown in Fig. 1(a), and the magnitude of fluid elastic normal stresses, $\sqrt{\tau_{p,xx}^2 + \tau_{p,yy}^2}$, normalized by the elastic modulus of the fluid, $G = \eta_p/\lambda$, is shown in Fig. 1(b). These plots correspond to the Weissenberg number of $Wi = 10$ and $L^2 = 20\,000$, where L is the maximum polymer extensibility, defined as the ratio of the length of polymer chain at a fully extended state and the root-mean-squared polymer length at the equilibrium state.

The physical nature of a mobile polymer macromolecule causes an extraordinary behavior of viscoelastic fluids. As a flexible polymer coil stretches within a flow field, an elastic restoring force results. This elasticity allows a fluid to carry stress along the flow streamlines, which can lead to the buildup of normal stresses in extensional flows like those in the wake of the cylinder, but also in simple shear flows like those in the boundary layer upstream of the cylinder. These elastic forces increase with increasing Weissenberg number and increasing molecular weight or finite extensibility of the polymer in solution. They can be observed as the magenta streaks in Fig. 1 and exist well into the far wake.

Due to the fluid's elasticity and the high finite extensibility of the polymer chains, the shear layers are significantly stretched before vortex shedding occurs, as shown in Fig. 1(a). The local extension rate within the flow plays a crucial role in the development of elastic normal stresses. As fluid elements approach the upstream stagnation point of the cylinder, they undergo compression in the streamwise direction, followed by significant stretching in the crossflow direction as they navigate around the cylinder. This extensional flow results in high extension rates, which in turn generate substantial elastic normal stresses in the vicinity of the upstream stagnation region as represented by the bright magenta bands in Fig. 1(b). These stresses, once developed, persist due to the fluid's finite relaxation time and are convected downstream along the cylinder surface and into the wake, as illustrated in Fig. 1(b). At a Weissenberg number of $Wi = 10$, the relaxation time of these stresses is large compared with the residence time of the flow, allowing their influence to extend far downstream from the cylinder.

Elevated elastic stresses are observed downstream in the shear layers, particularly between adjacent vortices and along their periphery, where the stretching of fluid elements remains pronounced. As a consequence, secondary vortices are formed when elastic stresses in the viscoelastic fluid pull parts of the shear layer into the wake, creating new vortices between the primary ones, as depicted in Fig. 1(a). Hence, in the wake of a cylinder placed in an inertial-viscoelastic fluid flow, we observe a *viscoelastic vortex street* that consists of two distinct vortex shedding modes: (i) primary vortices shed from the lateral sides of the cylinder, similar to those observed in Newtonian flows, and (ii) secondary vortices that emerge between the primary vortices, originating exclusively from the viscoelastic effects of the fluid. In these viscoelastic vortex streets, the primary vortices are strongly intertwined due to the existence of the secondary vortices. These additional vortices weaken the strength and coherence of the primary vortex street, disrupting the regular shedding that drives VIV, and as a result, they play a crucial role in suppressing structural oscillations.

Figures 1(d), 1(f), and 1(h) illustrate the buildup of elastic normal stresses near the cylinder as the finite extensibility of the polymer chains increases ($L^2 = 1000, 5000$, and $20\,000$). At the upstream stagnation region, rapid stretching of fluid elements in the crossflow direction results in high local extension rates, reaching $\dot{\epsilon} \approx 70 \text{ s}^{-1}$ for $L^2 = 20\,000$. These large extension rates lead to a significant buildup of elastic normal stresses near the upstream stagnation region of the cylinder that get swept into the wake. With increasing finite extensibility and elastic stress, the onset of vortex shedding is progressively delayed downstream from the cylinder, eventually leading to complete suppression of VIV [16,17].

Further insight into viscoelastic vortex streets is provided by the viscoelastic Mach number, defined as $Ma_e = \sqrt{Re Wi}$, which represents the ratio of the local flow speed to the speed of elastic wave propagation in a fluid. For viscoelastic Mach numbers greater than 1, $Ma_e > 1$, the flow velocity is faster than the propagation speed of an elastic wave, and information about the state of the elastic stress cannot be diffusively communicated upstream. For the cases shown in Fig. 1, $Ma_e \approx 28 \gg 1$, indicating the potential for viscoelastic shocklike behavior [18]. This manifests itself as a stagnation region with near-zero velocity, that forms a finite separation between the upstream cylinder surface and the shear layer [Fig. 1(g)]. This results in an expanded recirculation bubble and a near solid-wall-like concentration of elastic stress in front of the cylinder. The stagnation point shifts upstream of the cylinder surface, resulting in a “near-stagnation zone”—a

region characterized by elevated elastic stresses and vanishing flow velocity that does not quite reach zero.

In summary, we investigate the influence of viscoelasticity on vortex shedding in the wake of a flexibly mounted cylinder placed in inertial-viscoelastic flow. The interplay between fluid inertia and elasticity leads to unique features such as upstream elastic stress buildup, secondary vortex formation, and a near-stagnation zone characterized by viscoelastic shockwavelike behavior. These effects fundamentally alter wake dynamics and vortex interactions, distinguishing the viscoelastic vortex street from its Newtonian counterpart. This study has potential applications in areas of flow control, flow stabilization, vibration control, and structural integrity in offshore and subsea infrastructure. A detailed parametric study of this work can be found in our recent publication [16].

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Data availability. The data supporting this study's findings are available within the article.

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