

Route to instability in viscoelastic flows via porous interfaces

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We identify an instability mechanism in pressure-driven viscoelastic channel flows bounded by porous walls. Unlike the elastoinertial center mode in impermeable channels or the classical porous-wall mode in Newtonian flows, the instability uncovered here is wall localized and arises from the coupling of polymeric stress transport with interfacial momentum leakage. Elastic normal stresses concentrate disturbances at the fluid-porous interface, while permeability simultaneously enables slip-driven stress amplification and dissipative leakage, producing a wall-confined elastoinertial mode. The resulting instability occurs at Reynolds and Weissenberg numbers well below classical thresholds and exhibits a nonmonotonic dependence on permeability. In the strongly elastic limit, the onset is governed by interfacial stress localization rather than inertial amplification, rendering inertia nonessential. These findings show that permeability not only shifts stability boundaries but also reorganizes the instability mechanism itself, establishing a boundary-driven route to transition in porous-bounded viscoelastic flows.

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I. INTRODUCTION

Viscoelastic channel flows can become unstable even at weak inertia, as elastic stresses interact with viscous dissipation to produce transitions absent in Newtonian fluids [1–3]. Classical analyses and experiments have identified elastoinertial center and Tollmien-Schlichting-type modes in impermeable channels [4–7]. However, the role of wall permeability remains largely unexplored, despite its ubiquity in natural and engineered systems such as capillary networks, filtration membranes, and microfluidic coatings [8,9]. In Newtonian channels, permeability modifies stability through slip and momentum leakage [9–11], but how these effects interact with polymeric stresses remains unclear. Instability and transition phenomena are also known to arise in particulate complex fluids, including noncolloidal suspensions in Taylor-Couette flow and thermally driven suspension systems, where particle-induced stresses and microstructural evolution can fundamentally alter the onset and nature of flow transitions [12–15].

In this article, we demonstrate that the coupling of viscoelasticity with wall permeability produces a qualitatively new instability: a wall-localized elastoinertial mode (EWM) confined to the fluid-porous interface. A wall-localized elastic instability has been discussed in related studies of viscoelastic channel flow. In the present work, the new elastic wall mode arises specifically from coupling at the fluid-porous interfaces

and is absent when the walls are impermeable, indicating that permeable boundaries provide the route to this instability. Using a two-domain Oldroyd-B/Darcy-Brinkman formulation (details are provided in Sec. S1 of the Supplemental Material [16]), we show that permeability and elasticity act as competing mechanisms. Elastic normal stresses promote oscillatory growth, while porous leakage dissipates disturbances through wall-normal momentum exchange. Their coupling reorganizes the eigenspectrum and generates an instability absent in impermeable viscoelastic flows [5,7] or Newtonian porous channels [17].

Most significantly, the critical Reynolds number decreases sharply with increasing elasticity, indicating that the instability becomes predominantly elastic in origin once permeability enables stress localization at the interface. Permeability thus transforms the wall from a passive boundary condition into an active participant in elastic energy exchange, redefining the route to instability in porous-bounded viscoelastic flows.

II. METHOD

We consider the pressure-driven flow of an incompressible viscoelastic fluid in a channel bounded by symmetric porous layers, as shown in Fig. 1. The free-flow region has half-width L , and each porous wall of thickness H is characterized by porosity ϵ and permeability κ . The fluid is modeled using the Oldroyd-B constitutive relation [18–20], the canonical framework for linear stability studies of elastoinertial instabilities in dilute polymer solutions [2,21]. The Oldroyd-B model captures finite relaxation time and normal stress differences, the essential ingredients for elastic instability onset, while retaining analytical transparency. Although the model predicts constant shear viscosity and unbounded extensional viscosity, these features do not affect the linear stability threshold examined here, which is governed by stress-velocity coupling

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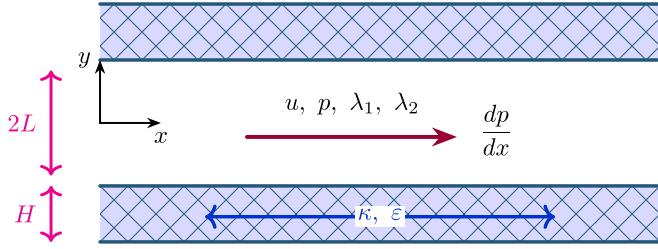


FIG. 1. Illustration of the computational domain and coordinate frameworks.

rather than nonlinear extensional saturation. More complex constitutive models, such as Giesekus, Phan-Thien-Tanner, and FENE-P [20,22–25], incorporate additional nonlinear mechanisms, including anisotropic mobility, shear thinning, or finite polymer extensibility. These effects introduce extra parameters that primarily influence nonlinear saturation and high-Wi dynamics. Establishing the instability threshold within the minimal Oldroyd-B framework, therefore, provides a baseline upon which such nonlinear refinements can be systematically assessed in future work. The dimensionless governing equations for continuity, momentum, and polymeric stress in the free-flow region are given by

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

$$\text{Re} \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \nabla \cdot \boldsymbol{\tau}, \quad (2)$$

$$\boldsymbol{\tau} + \text{Wi} \overset{\nabla}{\boldsymbol{\tau}} = 2(\mathbf{D} + \beta \text{Wi} \overset{\nabla}{\mathbf{D}}), \quad (3)$$

where $\mathbf{u}$ is the velocity, p is the pressure, $\boldsymbol{\tau}$ is the polymeric stress, and $\mathbf{D} = (\nabla \mathbf{u} + \nabla \mathbf{u}^T)/2$ is the strain-rate tensor. Here, $\boldsymbol{\tau}$ denotes the polymeric extra-stress tensor. The total stress in the Oldroyd-B model is given by $-p\mathbf{I} + 2\beta\mathbf{D} + (1 - \beta)\boldsymbol{\tau}$ (in nondimensional form). The Reynolds and Weissenberg numbers are defined as $\text{Re} = \rho U_{\max} L / \eta$ and $\text{Wi} = \lambda_1 U_{\max} / L$, where λ_1 is the polymer relaxation time, $\lambda_2 = \beta \lambda_1$ is the retardation time, and $\beta = \eta_s / \eta$ denotes the solvent-to-total viscosity ratio (η_s is solvent viscosity and η is total viscosity). The derivative in the upper part is $\overset{\nabla}{(\bullet)} = \frac{\partial(\bullet)}{\partial t} + \mathbf{u} \cdot \nabla(\bullet) - (\nabla \mathbf{u})^T \cdot (\bullet) - (\bullet) \cdot \nabla \mathbf{u}$. Within each porous wall ($j = 1, 2$), we employ the modified Darcy-Brinkman-Oldroyd-B [26], a well-established extension that introduces viscoelastic polymeric stresses into the momentum balance for flows in porous media via local volume averaging. Full derivation details are provided in Secs. S1 and S2 of the Supplemental Material [16], stated as

$$\nabla \cdot \mathbf{u}_{m,j} = 0, \quad j = 1, 2, \quad (4)$$

$$\begin{aligned} \text{Re} \left(1 + \text{Wi} \frac{\partial}{\partial t} \right) \frac{d\mathbf{u}_{m,j}}{dt} = & -\epsilon \left(1 + \text{Wi} \frac{\partial}{\partial t} \right) \nabla p_{m,j} \\ & + \left(1 + \text{Wi} \beta \frac{\partial}{\partial t} \right) \nabla \cdot \boldsymbol{\tau}_{m,j} \\ & - \epsilon \alpha^2 \left(1 + \text{Wi} \beta \frac{\partial}{\partial t} \right) \mathbf{u}_{m,j}, \end{aligned} \quad (5)$$

$$\boldsymbol{\tau}_{m,j} + \text{Wi} \overset{\nabla}{\boldsymbol{\tau}}_{m,j} = \frac{2}{\epsilon} (\mathbf{D}_{m,j} + \beta \text{Wi} \overset{\nabla}{\mathbf{D}}_{m,j}), \quad (6)$$

where $\alpha = L/\sqrt{\kappa}$ is the permeability parameter and the subscript m denotes the porous medium. The porous walls are modeled as homogeneous, isotropic, and rigid, and porosity is incorporated through the effective viscosity η/ϵ [27]. At each fluid-porous interface, the velocity and total stress are continuous, with a zero momentum transfer coefficient and negligible streamwise normal stress [28–30]. The geometric ratio $\delta = H/L$ defines the relative wall thickness. This formulation directly couples the polymeric stress field in the free fluid to momentum exchange within the porous layers, avoiding empirical slip laws.

In a steady base state, the free-flow velocity is parabolic, $U(y) = U_c - y^2$, where the centerline velocity U_c depends on the porous layer permeability, porosity, and geometry. In the porous layers, the nondimensional velocity profile is given by $U_{m,j}(y) = A_j e^{\sqrt{\epsilon} \alpha y} + B_j e^{-\sqrt{\epsilon} \alpha y} + \frac{2}{\alpha^2}$, with A_j and B_j set by interfacial conditions [31–33]. Although the velocity field mirrors its Newtonian counterpart, the dimensionless viscoelastic base-state stress is nontrivial. The base-state stress is $\bar{\tau}_{xx} = 2\text{Wi}(\frac{\partial U}{\partial y})^2(1 - \beta)$ in the free-flow region, and in the porous layers, it modifies to $2\frac{\text{Wi}}{\epsilon}(\frac{\partial U_{m,j}}{\partial y})^2(1 - \beta)$. To explore transitions from almost impermeable to highly permeable regimes, we fix porosity $\epsilon = 0.6$ and depth ratio $\delta = 1$, and vary the permeability parameter $\alpha \in [50, 500]$.

To assess temporal stability, we impose infinitesimal perturbations of the form $f(x, y, t) = f(y)e^{ik(x-ct)}$, where $c = c_r + ic_i$ is the complex wave speed and k is the streamwise wave number; instability occurs when $c_i > 0$. Here, $c = c_r + ic_i$ denotes the complex wave speed, while U_c is used for the base-flow centerline velocity. The Squire theorem states that the least stable disturbances in parallel shear flows are two dimensional [34]. Squire-type reductions have also been discussed for Oldroyd-B channel flows [35]. Motivated by these results and consistent with prior linear stability studies of viscoelastic channel flows, we restrict the present analysis to two-dimensional disturbances. The resulting eigenvalue problem is solved by Chebyshev spectral collocation [36], following our previous approaches [27,37–39]. Details of linearization, interfacial conditions, boundary conditions, and convergence tests are provided in Secs. S1 and S2 of the Supplemental Material [16]. The formulation reproduces benchmark results for the Oldroyd-B flow in impermeable channels [7,40] and the Newtonian flow in porous channels [17].

III. RESULTS

Unless otherwise stated, results are presented at $\text{Re} = 600$, $\beta = 0.8$, and representative wave number $k = 1.5$. The permeability parameter α is varied from 50 to 300, and eigenspectra are computed at weak ($\text{Wi} = 0.06$) and strong ($\text{Wi} = 61$) elasticity. The choice $k = 1.5$ lies within the peak-growth range reported for both Newtonian classical porous-wall mode Tollmien–Schlichting Mode (TSM) [41] and elastoinertial center mode (ECM) in impermeable channels [7,42], enabling direct comparison and clear identification of mode localization and branch interaction.

At weak elasticity ($\text{Wi} = 0.06$), Fig. 2 shows that even modest permeability reorganizes the eigenspectrum

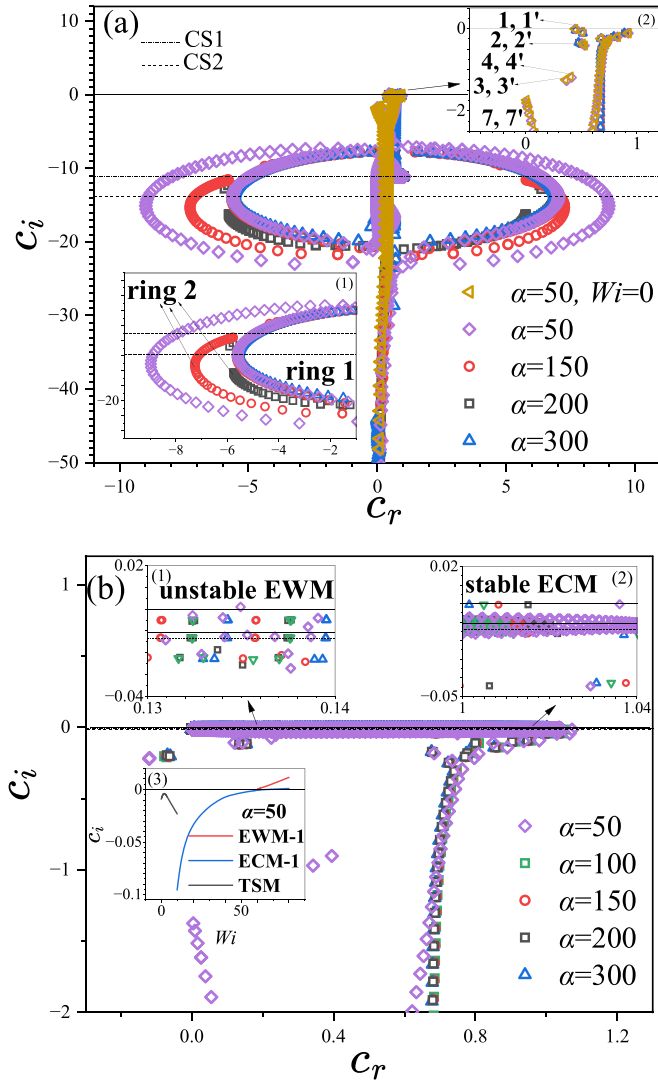


FIG. 2. Effect of wall permeability (α) on the eigenspectrum in the complex phase-speed plane ($c_r + ic_i$) at fixed $k = 1.5$. Parameters: $\varepsilon = 0.6$, $\delta = 1$, $\beta = 0.8$, and $\text{Re} = 600$. (a) Weak elasticity ($\text{Wi} = 0.06$): Increasing α suppresses the outer spectral ring and stabilizes wall branches. (b) Strong elasticity ($\text{Wi} = 61$): The wall-localized elastoinertial mode (EWM-1) becomes unstable at intermediate α and restabilizes as α increases. The solid line $c_i = 0$ separates stable and unstable modes. Insets show continuous spectra CS1 ($c_i \approx -1/(\beta\text{Wi})$) and CS2 ($c_i \approx -1/(k\beta\text{Wi})$).

compared to impermeable or Newtonian channels. The classical Tollmien-Schlichting (TS) and wall modes (1–4) are shifted and relabeled as 1'–4' in inset (2), reflecting viscoelastic modification. In addition, the porous-wall branch (mode 7), known from Newtonian permeable flows [17], appears as a damped vertical branch, where its viscoelastic counterpart (7') exhibits additional stress-induced alteration. Nonprimed modes denote Newtonian reference branches, and primed modes indicate their viscoelastic counterparts.

As Wi increases, the growth rate (c_i) of the Newtonian-like branches decreases, and portions of the spectrum merge toward the continuous spectra (CS1, CS2) characteristic of impermeable viscoelastic channels [7]. For finite Wi and

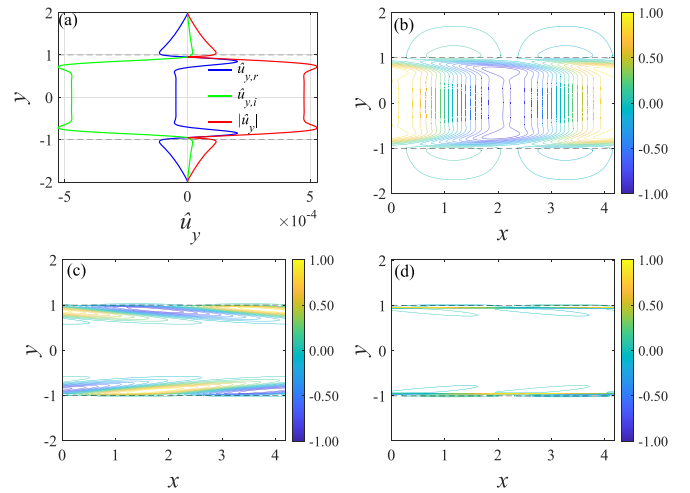


FIG. 3. Eigenfunctions of the dominant (most unstable) elastoinertial wall mode (EWM-1) at $\text{Re} = 600$, $k = 1.5$, $\text{Wi} = 61$, $\beta = 0.8$, and $\alpha = 50$ (eigenvalue $c = 0.13496 + 0.00099i$). (a) Wall-normal velocity eigenfunction $\hat{u}_y$ (magnitude, real, and imaginary parts). (b)–(d) Contours of wall-normal velocity ($\hat{u}_y$), streamwise velocity ($\hat{u}_x$), and streamwise polymeric normal stress ($\hat{\tau}_{xx}$). The mode is the least stable eigenvalue and exhibits strong localization at the fluid-porous interface.

$\alpha = 50$, permeability generates an additional outer ring of discrete modes (“ring 2”), encircling the classical ring 1 and continuous branches. This hybrid structure reflects the coupled action of elastic stress feedback and porous dissipation. Although these ringlike branches remain linearly stable in the weak-elasticity regime, their importance lies in the permeability-induced reorganization of the eigenspectrum: They embody the interaction between the continuous viscoelastic spectrum and interfacial momentum exchange and serve as spectral precursors to the elastoinertial wall mode (EWM-1) that emerges at higher elasticity.

As α increases (Fig. 2), ring 2 contracts, the leading eigenvalues shift toward more negative c_i (enhanced interfacial damping), mode 7' is progressively stabilized, and—at high elasticity—the EWM-1 branch moves closer to neutrality. These spectral shifts demonstrate that permeability promotes wall-normal momentum leakage into the porous layer, weakening wall-bulk coupling. Consequently, perturbation energy is increasingly dissipated within the substrate rather than reinforcing interfacial elastic growth, thereby delaying the onset of elastoinertial instability. The strong localization of EWM-1 near the fluid-porous interface (Fig. 3) confirms this mechanism.

At high elasticity ($\text{Wi} = 61$), a new wall-localized mode denoted the elastoinertial wall mode (EWM-1) [Fig. 2(b), inset (1)]. Unlike the classical ECM in impermeable channels [7,43] or the porous-wall mode in Newtonian permeable flows [17], EWM-1 originates directly at the fluid-porous interface and becomes unstable beyond a critical Wi , demonstrating that it is a distinct elastoinertial interfacial instability rather than a viscoelastic continuation of the classical porous-wall mode. This mode exists only when polymeric stress transport and interfacial momentum exchange act simultaneously. Elastic normal stresses concentrate disturbances at the boundary,

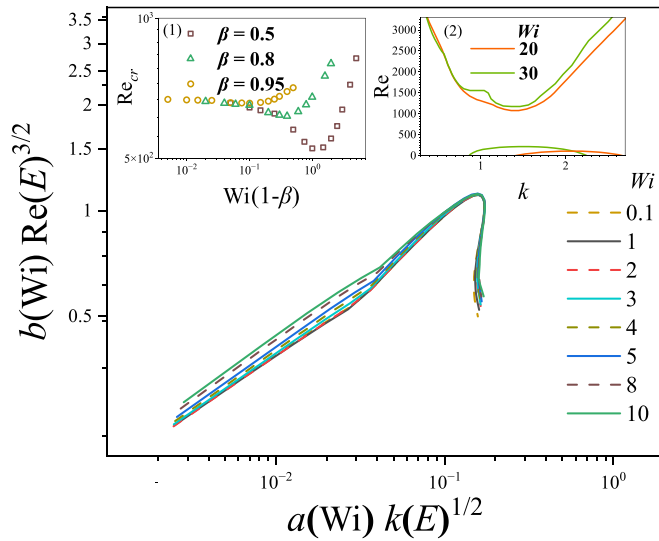


FIG. 4. Rescaled neutral stability curves plotted as $b(Wi) \text{Re}(E)^{3/2}$ vs $a(Wi) k E^{1/2}$ for varying Wi at fixed $\alpha = 50$ and $\beta = 0.8$. Inset (1): Re_{cr} vs $Wi(1-\beta)$, showing a Newtonian-like plateau, an intermediate dip from elastoinertial coupling, and restabilization at high elasticity. Inset (2): For $Wi \gtrsim 10$ ($Wi = 20, 30$), neutral curves deviate from the collapse, indicating the emergence of a distinct elastic wall mode (EWM) associated with the long-wave (low- k) branch. The high- k (short-wave) branch asymptotes to $\text{Re} \propto k^3$ in the strongly elastic limit, consistent with the elastoinertial center mode (ECM-1) in impermeable channels [7,44]. Permeability modifies prefactors but preserves this scaling for the bulk branch.

while permeability converts this stress localization into kinetic growth through slip-mediated feedback. The wall thus ceases to be a passive boundary condition and instead becomes the primary site of instability generation.

Permeability plays a dual and decisive role. At intermediate α , interfacial slip promotes elastic stress accumulation and amplifies the mode; at higher α , increased leakage diffuses disturbances into the porous substrate, disrupting stress concentration and suppressing instability. This nonmonotonic response reveals a direct competition between elastic energy storage and boundary-mediated dissipation. In particular, as elasticity increases, the instability threshold approaches the impermeable-channel limit even as inertial contribution diminishes, demonstrating that interfacial elastic stress localization, not inertia, controls the onset in this regime. In contrast to canonical shear-flow instabilities, where inertia or bulk elasticity governs transition, here the mechanism is boundary driven.

Increasing α reduces the growth rate of EWM-1 and ultimately restabilizes the flow, confirming that stronger permeability disrupts the interfacial stress concentration sustaining the mode. Neutral stability curves (Fig. 4) reveal a clear nonmonotonic dependence on α : Intermediate permeability lowers the critical threshold through slip-enhanced elastic feedback, whereas higher permeability raises it through dissipative leakage. This restabilization persists when optimizing over all wave numbers, with the global critical Reynolds number increasing with α in the regime where EWM-1 controls the onset. Permeability, therefore, acts not merely as a

boundary modifier but as an active regulator of the instability mechanism itself.

Inset (3) of Fig. 2 quantifies the evolution of the dominant branches (TSM, ECM-1, and EWM-1) with increasing Wi at fixed $\text{Re} = 600$, $k = 1.5$, $\beta = 0.8$, and $\alpha = 50$. The TSM remains stable, ECM-1 strengthens but remains damped, whereas EWM-1 detaches from the continuous branch and becomes unstable near $Wi \approx 60$, marking the onset of the wall-driven elastoinertial instability.

We now examine the impact of elasticity and solvent viscosity on the neutral stability of Oldroyd-B fluids in channels with porous walls, fixing permeability at $\alpha = 50$ (Fig. 4). For each fixed Wi in the range $Wi \in [0.1, 30]$ and $\beta = 0.5, 0.8, 0.95$, we compute the neutral curve $\text{Re}_n(k; Wi)$ from $c_i(\text{Re}, Wi, k) = 0$. Here, $\text{Re}_n(k; Wi)$ is the local Reynolds number along the neutral boundary, where the growth rate vanishes at wave number k . The global critical Reynolds number is then $\text{Re}_{\text{cr}}(Wi) = \min_k \text{Re}_n(k; Wi)$ and the elasticity number is denoted as $E = Wi/\text{Re}$. To reveal self-similar structure across Wi and β , we rescale the neutral curves using empirically determined functions $a(Wi)$ and $b(Wi)$ that collapse the weak Wi dependence. When plotted as $b(Wi)\text{Re}^{3/2}$ versus $a(Wi)kE^{1/2}$, all data collapse onto a single master curve, yielding the similarity relation

$$\text{Re}(E, k, Wi) = E^{-3/2} b(Wi)^{-1} F(a(Wi) k E^{1/2}). \quad (7)$$

The collapse procedure is detailed in Sec. S4 of the Supplemental Material [16], where $a(Wi)$ and $b(Wi)$ are obtained across the parameter range. In the strongly elastic limit ($Wi \gg 1$), $a(Wi), b(Wi) \rightarrow 1$, and the master curve exhibits a short-wave asymptotic slope corresponding to

$$\text{Re} \propto k^3, \quad (8)$$

reflecting a balance between elastic normal-stress gradients and inertia. This scaling is consistent with the ECM in the impermeable-channel studies [7,44]. Permeability parameter modifies the prefactors via interfacial dissipation, but preserves the functional form of the dominant wall-localized branch.

More generally, if the universal curve has local slope m , the scaling becomes $\text{Re} \propto k^{\frac{2m}{m-1}}$, with explicit Wi dependence absorbed into $a(Wi)$ and $b(Wi)$. The neutral curves exhibit two distinct branches: a short-wave elastic bulk mode (ECM-1) and a long-wave porous-wall mode (EWM-1). This elastoinertial bimodality extends the Newtonian porous-wall bimodality [27,41,45] by incorporating polymeric stresses, which shift dominance to the wall-localized mode at high Wi via interfacial elastic feedback. The resulting nonmonotonic dependence on $Wi(1-\beta)$ and tunable permeability effect, absent in impermeable viscoelastic channels, highlights a physical competition between elastic stress storage (promoting wall instability) and porous dissipative leakage (suppressing it). Inset (1) of Fig. 4 shows the variation of Re_{cr} with the combined elastic-viscous parameter $Wi(1-\beta)$. For small $Wi(1-\beta)$, Re_{cr} approaches the Newtonian limit. At intermediate values, Re_{cr} exhibits a shallow minimum due to constructive elastoinertial coupling. At large $Wi(1-\beta)$, Re_{cr} increases as elastic stress gradients saturate, most prominently for $\beta = 0.95$, where higher solvent viscosity suppresses

short-wavelength disturbances. These regimes highlight the nonuniversal dependence of the critical threshold on the combined effects of elastic and viscous forces.

Inset (2) shows a high-wave-number instability emerging at large Wi for moderate permeability ($\alpha = 50$). At low Wi , the flow remains stable, but increasing Wi excites an EWM from the continuous spectrum that becomes unstable for $k \gtrsim 1.5$. This secondary dip in the neutral curve signals a transition from a viscous-inertial to a wall-localized elastic mechanism. Unlike impermeable channels where the ECM dominates [7], permeability suppresses bulk modes and promotes EWM through wall slip and elastic stress concentration. Additional trends with varying permeability are provided in Sec. S4 of the Supplemental Material [16].

These results extend the Newtonian findings of Tilton and Cortezzi, who reported that for highly permeable walls ($\alpha \sim 5000$) the instability threshold differs by less than 0.3% from the classical Poiseuille value. In contrast, our analysis focuses on the intermediate-to-high permeability range ($\alpha = 50$ –100), where viscoelastic effects significantly alter the stability threshold and highlight the coupled role of elasticity and permeability. Direct comparison has been reported in the Supplemental Material [16]. Porous walls also significantly affect how polymeric stresses influence flow stability. A detailed analysis of how polymeric elasticity influences the onset and structure of the instability, including the nonmonotonic dependence of the critical Reynolds number on $Wi(1 - \beta)$, is presented in Sec. S4 of the Supplemental Material [16].

IV. CONCLUSIONS

We demonstrate that wall permeability fundamentally reorganizes instability in viscoelastic shear flows. Rather than merely shifting classical thresholds, permeability transforms the boundary into an active site of elastic energy exchange, generating a wall-localized instability absent in impermeable channels. Instability is initiated and sustained through interfacial stress localization coupled to momentum leakage into the porous substrate. Permeability, therefore, acts as a fourth control parameter, alongside Re , Wi , and β , governing both the onset and structure of unstable modes. Similar modifi-

cations of instability thresholds by porous boundaries have recently been observed in particle-laden Couette-Poiseuille flows, highlighting the broader role of porous interfaces as active regulators of flow transitions in complex-fluid systems [46]. More broadly, these findings challenge a central premise of canonical stability theory—that boundaries only modify thresholds without altering mechanisms. Together with recent observations of suspension-driven transitions in Taylor-Couette and porous-wall particle-laden flows, the present results suggest that interfaces, microstructure, and elasticity may provide alternative pathways to instability beyond the classical Newtonian paradigm [12,14,46]. Here, the boundary participates directly in the energy pathway that drives transition. Instability is no longer solely a bulk competition between inertia and elasticity, but a boundary-mediated process shaped by interfacial transport. Unlike Newtonian porous flows, where permeability introduces slip without changing the instability class, viscoelastic permeability generates a distinct instability branch with unique localization and scaling.

The emergence of this elastoinertial wall mode and its nonmonotonic dependence on permeability demonstrate that interfaces can act as generators—not merely modulators—of instability, extending the classical framework of shear-flow transition to porous-bounded complex fluids.

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P.M. conceived the project, supervised the research, interpreted the results, and wrote the manuscript. E.T. performed the theoretical analysis and numerical simulations, and assisted in revising the manuscript.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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