Hydrodynamic Stability Analysis on a Class of Complex Flow Systems

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ABSTRACT

Hydrodynamic instability plays a central role in governing the transport of mass, momentum, and energy in a wide range of natural and industrial fluid systems. Such instabilities may arise from the complex interaction of shear, buoyancy, rotation, magnetic fields, medium heterogeneity, and time-dependent forcing. They often dictate the transition from a laminar to a turbulent flow state. Despite extensive classical studies, the mechanisms underlying instability and control strategies in complicated flow environments, including rotating channel flows, flows in anisotropic and inhomogeneous porous media, magnetohydrodynamic (MHD) flows, and vibrated bounded and semi-bounded flow systems, have yet to be comprehensively explored. The primary objective of this thesis is to develop a mathematical framework for investigating hydrodynamic instabilities and associated active/passive control mechanisms across these flow configurations. In this thesis, we systematically analyze (i) the instability characteristics in channel flows through anisotropic porous media under spanwise system rotation, with and without MHD influence; (ii) the modal and non-modal behavior to identify dominant instability mechanisms and optimal transient energy amplification under directional and spatial variation in permeability; and (iii) the effects of system vibration and odd viscosity in free-surface flows, as well as the combined influence of system vibration and velocity slip in channel flows, to elucidate their roles in parametric and shear-driven instabilities.

The Darcy–Brinkman formulation is employed to address porous media models, accounting for variations in permeability, anisotropy, and inhomogeneity, with additional relevant terms for Coriolis or Lorentz forces. The influence of key nondimensional parameters, including the Reynolds number, rotation number, porous shape factor, permeability ratio, Hartmann number, and viscosity ratio, is systematically examined. The results demonstrate that Coriolis force–driven rotational instabilities can be effectively controlled through anisotropic permeability of the porous medium. Further investigation into the MHD-induced rotating porous system reveals that Lorentz forces associated with the applied magnetic field delay the onset of rotational instability due to additional Joule damping. These combined effects are shown to play an important role in determining the stability characteristics of rotating machinery, geophysical flows, and electrically conducting porous systems. Both modal and non-modal stability frameworks are employed to analyze anisotropic and inhomogeneous flow systems. While modal analysis identifies classical exponential instability modes, non-modal analysis reveals transient growth mechanisms arising from the non-self-adjoint nature of the governing operators. The results highlight how anisotropies and spatially varying inhomogeneous permeability can alter critical instability thresholds, promote significant energy amplification, and reshape the transient response of the system. Finally, instabilities induced by system vibrations in free-surface and channel flows are investigated, with direct relevance to thin-film transport, coating processes, electro-hydrodynamic devices, and bio-inspired fluid propulsion. Using Floquet theory and perturbation analysis, the study examines how substrate vibration triggers parametric resonant and shear-driven instabilities, alters wave dynamics, and influences the onset of flow transition. The competing roles of wall vibration, surface tension, gravity, and velocity slip are investigated to determine the conditions under which flow disturbances either amplify or decay.

Overall, this thesis provides a coherent understanding of hydrodynamic instability behavior across porous, rotating, magnetohydrodynamic, oscillating, and free-surface flow environments. The findings offer both theoretical insight and practical guidance for controlling instability in filtration devices, rotating machinery, microfluidic systems, turbo-machinery cooling channels, coating technologies, and vibration-driven transport processes.

List of Publications/Pre-prints

Publications included in the thesis:

1. **M. Saha**, S. Sengupta, S. Mukhopadhyay, and S. Ghosh, “Flow instability in a rotating channel loaded with an anisotropic porous material,” **Computer & Fluids**, vol. 299, pp. 106689, 2025. `https://doi.org/10.1016/j.compfluid.2025.106689`

2. M.M. Hossain, **M. Saha**, S. Ghosh, and H. Behera, “Stability dynamics of an odd-viscosity induced fluid flow over a vibrating inclined surface,” **Physics of Fluids**, vol. 37(10), pp. 104108, 2025. `https://doi.org/10.1063/5.0291294`

3. **M. Saha**, and S. Ghosh, “On the magnetohydrodynamic instability pattern of an anisotropic porous media flow in a rotating channel,” **Physics of Fluids**, vol. 38(1), pp. 014122, 2026. `https://doi.org/10.1063/5.0307689`

4. **M. Saha**, M.M. Hossain, and S. Ghosh, “Linear instability of an oscillating hydrophobic channel flow.” (Under review)

5. **M. Saha**, S. Ghosh, M. Roy, and M. Mishra, “Modal and non-modal stability of Poiseuille flow through anisotropic inhomogeneous porous materials.” (Ready for Submission)

Publications out of the thesis:

6. **M. Saha**, S. Ghosh, and K. C. Sahu, “Dual instability in a crossflow-induced oscillating channel flow.” (Ready for Submission)

7. S. Panda, **M. Saha**, and S. Ghosh, “Effect of uniform vertical crossflow on rotational instability in a channel flow.” (In preparation)

Presentations in Conferences

1. Presented a paper entitled “Hydrodynamic Instability of Flow Through a Rotating Channel Filled with Anisotropic Porous Media” at the **International Conference on Recent Advances in Fluid Mechanics and Nanoelectronics (ICRAFMN-2023)**, Manipal Institute of Technology, Bengaluru, India.
2. Presented a paper entitled “Influence of magnetic field on instability of the flows in a rotating channel filled with anisotropic porous substrate” at the **78th Annual Meeting of the APS Division of Fluid Dynamics (APS DFD-2025)**, Houston, Texas, USA.