VORTEX FLOW STABILITY, DYNAMICS AND FEEDBACK STABILIZATION

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ABSTRACT

A theoretical and computational study of the stability, dynamics and feedback stabilization of swirling flows in a pipe is proposed. The theoretical analysis is based on developing a new reduced-order, weakly-nonlinear model equation of the complex dynamics of small perturbations on a columnar flow at near-critical swirl levels where a natural instability and transition to vortex breakdown may occur. The model also includes perturbations to the inlet circulation, inlet flux and pipe radius variations that may be used as control parameters of the flow dynamics. The model is first used to study the bifurcation of equilibrium states at swirl levels near critical and the stability of these states at both inviscid and high Reynolds number flow cases. The response of a perturbed columnar flow to various initial perturbations at various swirl levels is computed using the weakly-nonlinear approach and direct numerical simulation codes. Results present agreements between theory predictions and simulations as long as perturbation size is small. However, as perturbation grows to establish a stagnation point in the flow, the weakly-nonlinear model predictions become singular and are not representative of flow dynamics. Results also show that perturbation dynamics to vortex breakdown is composed of several stages, including the linear growth of perturbation followed by the weakly-nonlinear growth, a stage of transition to breakdown, and a stage of decay to the breakdown state. Specifically, the stage of the weakly-nonlinear growth of perturbations is characterized by faster-than-exponential, shape-changing axial modes which provides the breakdown process its abrupt and sudden nature. The stages of transition to breakdown and decay to a breakdown state are characterized by lateral and axial modes of evolution that cannot be described the present weakly-nonlinear theory. The weakly-nonlinear model is also used as a tool to design feedback stabilization/control methodologies and prevent the evolution of a swirling flows with above critical swirl level from transition to breakdown for both inviscid and high Reynolds number swirling flows. This study also sheds light on the control of the KdV equation with nonperiodic inlet-outlet boundary conditions and it may be extended to other fields of science.