DOCTORAL THESIS IN ENGINEERING MECHANICS
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Studies on instability and optimal forcing of incompressible flows

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Abstract

This thesis considers the hydrodynamic instability and optimal forcing of a number of incompressible flow cases. In the first part, the instabilities of three problems that are of great interest in energy and aerospace applications are studied, namely a Blasius boundary layer subject to localized wall-suction, a Falkner−Skan−Cooke boundary layer with a localized surface roughness, and a pair of helical vortices. The two boundary layer flows are studied through spectral element simulations and eigenvalue computations, which enable their long-term behavior as well as the mechanisms causing transition to be determined. The emergence of transition in these cases is found to originate from a linear flow instability, but whereas the onset of this instability in the Blasius flow can be associated with a localized region in the vicinity of the suction orifice, the instability in the Falkner−Skan−Cooke flow involves the entire flow field. Due to this difference, the results of the eigenvalue analysis in the former case are found to be robust with respect to numerical parameters and domain size, whereas the results in the latter case exhibit an extreme sensitivity that prevents domain independent critical parameters from being determined. The instability of the two helices is primarily addressed through experiments and analytic theory. It is shown that the well known pairing instability of neighboring vortex filaments is responsible for transition, and careful measurements enable growth rates of the instabilities to be obtained that are in close agreement with theoretical predictions. Using the experimental baseflow data, a successful attempt is subsequently also made to reproduce this experiment numerically.

In the second part of the thesis, a novel method for computing the optimal forcing of a dynamical system is developed. The method is based on an application of the inverse power method preconditioned by the Laplace preconditioner to the direct and adjoint resolvent operators. The method is analyzed for the Ginzburg−Landau equation and afterwards the Navier−Stokes equations, where it is implemented in the spectral element method and validated on the two-dimensional lid-driven cavity flow and the flow around a cylinder.

Key Words

hydrodynamic stability, optimal forcing, resolvent operator, Laplace preconditioner, spectral element method, eigenvalue problems, inverse power method, direct numerical simulations, Falkner−Skan−Cooke boundary layer, localized roughness, crossflow vortices, Blasius boundary layer, localized suction, helical vortices, lid-driven cavity, cylinder flow.

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