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Computational Modelling of Bifurcations and Instabilities in Fluid Dynamics

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Preface

Instabilities of fluid flows and bifurcations between them comprise a fascinating set of problems that have attracted researchers for over a hundred years. The first fluid flow instabilities were studied starting from the second half of the nineteenth century by Kelvin, Helmholtz, Rayleigh, Taylor and others. In the pre-computer era, only analytical studies were possible, and hence necessarily focused on instabilities of simple one-dimensional plane-parallel flows. Nevertheless, the instability criteria (e.g. Rayleigh inflection point criterion) and some basic instability mechanisms (e.g. Kelvin–Helmholtz and Rayleigh–Bénard instabilities) discovered at these early stages are still used to explain incomparably more complicated two- and three-dimensional results.

The availability of the first computers for numerical modelling, starting from the 1970s, led to the implementation of numerical analysis tools in stability studies. Although the base states considered were still one-dimensional, more complicated problems were considered. One of the most well-known results of that time is the calculation of the critical Reynolds number for plane channel (Poiseuille) flow, and strong evidence of the absence of linear instability in plane Couette and circular Poiseuille flows. Another example is the instability of boundary layers due to Tollmien–Schlichting waves.

Rapid growth of computational power allowed the study of two-dimensional base states in the mid-1980s and 1990s. The two-dimensional base states must be calculated numerically with the subsequent solution of the eigenvalue problem associated with the linear (modal) stability of the base flow. At this stage, more complicated methods of numerical linear algebra started to be applied. Krylov subspace iteration actively developed at the same time brought additional possibilities for computational modelling of fluid flow instabilities. The most popular problems considered were Taylor–Couette flow and convection in cavities. Simultaneously, the importance of fluid flow instabilities was recognized for various material processing technologies, leading to experiments in microgravity, which in turn motivated related numerical studies that included instability problems.

At the same time, non-modal growth at short times was applied and popularized and the mathematical apparatus needed to address it was developed. The experimental and numerical discovery of fluid flow bifurcations revived interest in weakly nonlinear analysis of bifurcations and slightly supercritical states, so that early results of Poincare and Hopf concerning ordinary differential equations were applied and extended. The need to compute steady states and instabilities at different governing parameters, and the existence of multiple steady and oscillatory states gave rise to path-continuation techniques that are now considered an essential tool for performing computational instability studies.

In parallel to these methods, bifurcations and instabilities were studied by straightforward time integration of the governing equations. While much simpler than the above-mentioned techniques, time integration misses possible multiplicity of states as well as unstable branches which play an important role in bifurcation diagrams, and is in addition incomparably more CPU time consuming, which strongly restricts parametric studies.

With further increase of computational power, formerly difficult computations became noticeably easier. As a result, the number of stability and bifurcation studies increased to the point that some leading fluid dynamics journals consider 'instabilities' to be a separate topic for classifying articles. Nevertheless, calculations of instabilities of fully three-dimensional flows remain challenging even with state-of-the-art approaches.

Modern studies of fluid flow instabilities are sharply divided into fundamental studies of idealized configurations, such as flows in rectangular, cylindrical or spherical containers, and applied studies that attack technologically motivated problems. The applied configurations are characterized by a much higher level of complexity and involve moving boundaries, phase change, double-diffusion, electrical and magnetic fields, etc. One example is the instability of plasma in tokamak fusion reactor. All these require the further development of computational techniques dedicated to modelling of bifurcations and instabilities in fluid dynamics.

The purpose of this review book is to assemble descriptions of most advanced numerical techniques, as well as to review some recently solved instability problems. We leave it to the reader to judge to what extent this goal has been achieved.

Tel Aviv, Israel Alexander Gelfgat

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