Fundamentals of transition — overview

Transition describes the physical process by which laminar flow goes through a cascade of instabilities and state-space changes before it settles into fully developed turbulent fluid motion. Despite remarkable progress (particularly with the advent of computational tools), many open questions about the details of transition to turbulence remain. Transition is commonly a fundamental research subject, but it is also important to applied engineering. The impact of transition on skin friction, drag, thermal loading, and mixing are only a few areas upon which the design of fluid devices critically depend. Understanding the underlying fundamental principles of transition is as important as the modeling of transition effects and their incorporation into a predictive framework.

The following seven reports are related to transition and its connection to ensuing turbulent flow. The first three projects applied different descriptive analyses to simulation databases of flat-plate boundary layer transition. The fourth aimed at control transition through optimal choice and placement of actuators. The fifth applied Stochastic Structural Stability Theory (SSST) to derive a quasi-linear model that captures both transition and the self-sustaining process supporting turbulent Couette flow. Finally, the sixth and seventh probed the physics of transitional and turbulent wall-bounded flows by examining how they are modified by the introduction of polymer additives.

The first project by Sayadi *et al.* aimed at isolating and quantitatively describing coherent structures that are principally responsible for the rise in wall friction during H-type transition in the flat-plate boundary layer. This study was motivated in part by the observation that the streamwise development of skin friction predicted by large eddy simulation (LES) deviates significantly from that predicted by direct numerical simulation (DNS). The dynamic mode decomposition (DMD) was chosen to analyze the two databases, where composite data vectors (containing both structural and output parts) were used to establish a link between coherent structures and their footprint in the skin friction profile. A reconstruction using only three low-frequency DMD modes (consisting of the hairpin legs only) accurately captured the DNS skin-friction field, and comparison to LES suggests the possibility of a DMD-based remedy for the LES subgrid-scale model in the vicinity of transition.

The second project by Bernardini *et al.* evaluated a large DNS database of transition in a compressible boundary layer induced by roughness elements of various cross-sectional shapes and dimensions. Transition under these conditions is dominated by the destabilization of streaks induced by horseshoe vortices forming about the roughness elements. DMD captured the dominant Strouhal number of this destabilization and showed varicose modal structures for larger Reynolds numbers, whereas sinuous modes prevailed further downstream at lower Reynolds numbers. A parameterization of roughness-induced bypass transition (using a momentum deficit argument) allowed the introduction of a Reynolds number which separated effects of roughness, obstacle geometry and obstacle aspect ratio, including the appropriate scaling, and for which the data showed remarkable collapse.

The third project by Nolan *et al.* was motivated by the observation that transition to turbulence is sporadic and localized: while streaks are ubiquitous in many transition experiments, only a few of them break down and induce transition whereas the bulk of them remain innocuous. A methodology for tracking individual streaks in space and time was developed, and the inception of turbulent spots (following the breakdown of the streak) was associated with individual parent streaks and used in a statistical evaluation of streak breakdown frequency. In a second step, the turbulent spot (from the breakdown of a streak) was also tracked in space and time using laminar-turbulent discrimination, showing that the spreading volume of the spot is independent of the pressure gradient. The combination of the two analyses provides a novel system to model and predict the onset of bypass transition for a range of relevant flow configurations.

The goal of the fourth project by Bodony *et al.* was the development and application of a general methodology to place actuators into a given flow field in order to manipulate the inherent flow behavior towards a user-specified objective in an efficient manner. The question of what type of controllers to choose and where to place them has many important applications in control design. As a test case, compressible flow in a diffuser inlet was modeled by a backward-facing ramp, and a stabilization of the unstable global mode was chosen as the control objective. The overlap of direct and adjoint solutions to the linearized governing equations produced sensitivity maps, which, when combined with a matrix optimization algorithm, provided a flexible and rational framework for actuator selection and placement.

The fifth project by Farrell *et al.* tested the correspondence with DNS data of turbulence structure and dynamics obtained using streamwise constant (2D/3C) and streamwise averaged (SSST) models. The 2D/3C model isolated turbulence dynamics to the interaction between roll structures and the mean flow. Comparison with DNS data verified that accurate turbulent mean flow statistics are obtained using this model when the roll structures are stochastically forced. Understanding how the roll and streak structures are consistently forced requires a model that augments 2D/3C dynamics with feedback from the streamwise constant mean flow back to the perturbation dynamics. With this additional feedback, SSST not only obtains accurate turbulence statistics but also captures the dynamics of transition to turbulence and the self-sustaining process maintaining the turbulent state. The SSST model was emulated using a quasi-linear (QL) model in which the dynamical restrictions of SSST were imposed on a DNS code. Comparison of DNS and QL data showed agreement in turbulence statistics as well as in transition and self-sustaining state dynamics.

The final two projects examined the role of polymer additives on transitional and turbulent flows. The project by Dubief *et al.* used DNS to study the role of elastic instabilities in inducing transition. Relative to Newtonian fluids, numerical experiments of a bypass transition in a channel flow showed that visco-elasticity can promote departure from laminar flow at lower Reynolds numbers. In the seventh project, Lieu & Jovanović demonstrated that the essential drag-reducing trends, previously observed in DNS, can be captured by a model-based approach. The developed approach utilizes turbulence modeling in conjunction with the analysis of stochastically forced linearized equations to determine the effect of flow fluctuations on the turbulent viscosity and drag.

In summary, the following seven reports are connected by a common vision that a better understanding of the fundamental processes governing the otherwise complicated phenomenon of transition is essential to the creation of more accurate models for prediction and control. Furthermore, as DNS databases become increasingly detailed and comprehensive, we are able to test our theories as never before.

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