Transition and turbulence: Prediction, control and optimization — overview

Transitional and turbulent flow is a fundamental aspect of nearly all engineering fluidic systems that can determine system efficiency and utility. Predicting and controlling transitional and turbulent flows is thus a critical application of fluid mechanics; however, the complexities permitted by the governing equations have so far resisted a general solution. Instead focused, hypothesis-driven analysis, enabled by novel algorithms for data prediction and assimilation, remains the primary means to affect how transitional and turbulent flows behave and how these findings are used to improve engineering designs.

The international 'transition and turbulence' group was assembled from ten world-renowned institutions, with each person focused on improving our means to understand, predict, and control transitional and turbulent flows. Three cross-cutting themes materialized over the course of the Summer Program, namely:

(*a*) Flow physics and modeling
(*b*) Passive control of wall turbulence
(*c*) Algorithms and tools for flow control and optimization.

At the most fundamental level there is still much that is unknown about transitional and turbulent flows and, in particular, how these flows interact with a surface. For example, the crossflow instability studied by Duan, Choudhari, and Li occurs on swept wing aircraft where the three-dimensional flow near the wing surface created by the wing sweep is susceptible to stationary vortices that become unstable and induce boundary layer transition. The instability is known to be very sensitive to the environment, and both direct numerical simulation and parabolized stability equations were used to ensure self-consistent transition predictions between the two models prior to examining the external sensitivity and possible control strategies. Bodony, on the other hand, examined how a fully turbulent Mach 2.25 boundary layer interacted with a compliant surface through direct numerical simulations of both the fluid and solid domains. Linear models of increasing fidelity were considered, and it was found that the panel-mean flow interaction was important and needed to be included for an accurate model.

Controlling wall-bounded turbulence to reduce drag can be accomplished in several ways, but how this occurs is not well known. Superhydrophobic surfaces, such as those studied by Garcia-Mayoral, Seo, and Mani, use a trapped layer of gas to reduce the effective wall shear stress seen by the liquid-phase grazing flow. Prior work ignored the dynamics of the liquid-gas interface, but, as Garcia-Mayoral *et al.* show, it is important and can lead to interfacial waves that travel against the bulk flow and show parametric dependencies that still need to be understood. When in a single phase environment, a similarly-constructed surface acts as an impedance boundary and, if properly optimized, can affect the turbulence immediately adjacent to it. Such was the hypothesis driving the simulations by Scalo, Bodart, Lele, and Joly where they find that a dramatic change in the turbulence is possible for suitably chosen impedance parameters. Optimization was also the focus of Talnikar, Blonigan, Bodart, and Wang, where the design of a aircraft engine turbine trailing edge motivates the use of a parallel Bayesian optimization algorithm suitable for a large-eddy simulation environment capable of efficiently handling the statistical noise-induced jitter of the objective function due to finite time simulations.

The optimization method efficiently utilizes massive concurrency by utilizing surrogate functions to select parameters to be tested simultaneously.

Simulating transitional and turbulent flows from first principles requires computational resources that are not usually available for control; instead, trustworthy reduced-order models that capture the essential dynamics and appropriate sensitivities are needed. Constructing such models is challenging and requires intelligent algorithms be combined with large data analysis tools and means to estimate parametric sensitivities. Sayadi and co-workers develop simultaneously new algorithms for computing the QR-algorithm necessary for many data reduction techniques and optimal estimation algorithms for reconstructing the wall stress from near-wall boundary layer dynamics. Sayadi, Hamman, and Schmid, for example, develop a parallel QR algorithm for tall-and-skinny matrices commonly found in dynamic mode decomposition of data sets with many spatial degrees of freedom but far fewer temporal snapshots and test it on a recent DNS database of H- and K-type transition. Optimal parameter estimation by several approaches are used by Sayadi and Schmid to develop transfer functions that are able to predict near-wall stresses from mean velocity statistics that aim to reduce computational cost of large eddy simulation in and around complex geometries. Zare, Jovanović, and Georgiou examined turbulence modeling as an inverse problem using stochastically forced linearized Navier-Stokes equations. They identified the necessary forcing statistics to match the DNS-based second-order turbulence statistics by solving a convex optimization problem, and observed that the “color” of the stochastic forcing is critical for accurate estimation.

The observation that parametric estimation by reduced-order models is often problematic leads Fosas de Pando, Schmid, and Lele to develop two complementary techniques. In one technique they use the Galerkin projection of proper-orthogonal-decomposition (POD) modes to generate two separate basis sets—one for the linear part and one for the nonlinear part—that is reduced in complexity but is able to accurately model nonlinear dynamics by greedily selecting the nonlinear basis to reproduce dynamical behavior at adaptively determined spatial locations. In their other paper, Fosas de Pando *et al.* develop a technique to estimate sensitivity of a given solution to parametric changes in the flow, such as Reynolds number or Mach number changes, by reinterpreting a specifically chosen adjoint solution to improve the amount of information available in complex parameter-dependent flows.

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