Multi-physics and Data-driven Studies — overview

Since 1987, the Summer Program of the Center for Turbulence Research has gathered a large community of turbulence researchers at Stanford University. The program originated as a means to exploit databases of large–scale simulations generated at NASA Ames Research Center. Over the last three decades, the analysis of data resulting from simulations, or collected from experiments, has been a critical component of turbulence research, either to generate and test ideas for modeling purposes or to clarify the physical processes in play. In pursuit of these goals, numerous data analysis techniques have been explored and, in many cases, have found broad applicability in other fields. Today, data science is attracting increasing attention in a variety of disciplines; the reports in this section represent research at the intersection of data science and turbulence.

The first group of four contributions revolved around the development and demonstration of novel algorithms for data analysis. Schmid *et al.* explored two novel strategies to identify and extract modes that contribute to intermittent and extreme behaviors in turbulent flows. Advanced data clustering techniques enabled the identification of extreme transitions in near–wall turbulence, while a conditioned POD highlighted acoustic bursts in supersonic heated jets. Bodony investigated the derivation of adjoint operators starting from experimental images on liquid jets for the purpose of controlling mixing. The approach includes elements of image analysis, feature extraction, and, ultimately, forecasting. Arza focused on modern inference techniques to assess the feasibility of autonomous navigation in complex fluid flows; he used reinforcement learning techniques to study source localization problems, that is, to identify the source of a contaminant using a local sensor that can navigate in a two-dimensional or three-dimensional field. Bermejo-Moreno *et al.* developed a sophisticated data analysis and feature-extraction technique and applied it to the study of the shock-turbulence interaction problem. The proposed approach enables the dynamical tracking of physical structures and constructs a graph of events relating different structures, such as break up or merge, that can be employed both forward and backward in time to assess causality relations.

The second group of four contributions investigated the application and improvement of existing data analysis techniques in challenging multi-physics applications. Tamm built a database of high-fidelity simulations of turbulent jets exhausting from military-style nozzles; his aim was to investigate the effect of inflow temperature non-uniformity on overall jet noise. In addition to detailed comparisons to available experimental data, he used spectral POD to identify changes in the most energetic modes. Blonigan *et al.* investigated the shadowing-based technique to compute adjoints in chaotic turbulent flows; they focused on lowering computational cost by selectively reducing the accuracy of the approach and tracking a limited number of unstable modes. Wang *et al.* investigated the use of geometrical modification to nozzle shapes to reduce overall jet noise; they built high-fidelity databases and used Lyapunov exponent analysis to investigate the most unstable modes. These modes provide insights into how changes in the geometry, such as serrations or chevons, lead to reduced noise generation by increasing mixing. Last, but not least, Gori *et al.* studied geometrical optimization of turbine blades to improve the performance of organic Rankine cycle compressors. The challenge in this case was to infer the properties of the working fluid (octamethyltrisiloxane, $C_8H_{24}Si_3O_2$)

from available experimental measurements of nozzle flows; they used Bayesian inference and incorporated the resulting fluid parameters together with their joint probability distribution in a probabilistic optimization strategy. The results illustrate how carefully designed blades can minimize the impact of fluid properties, uncertainties on the overall turbine operation.

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