

Analysis of Turbulent Boundary Layers group: overview

Turbulent boundary layers play a key role in a wide range of natural and engineered flows. The atmospheric boundary layer mediates many of the most crucial phenomena for understanding weather and climate patterns, including natural disasters such as wildfires and hurricanes. Aquatic wildlife such as sharks and dolphins have long been admired for their low drag and high swimming velocities. Transition to turbulence is costly for many aerodynamic and hydrodynamic vehicles, from civilian and military aircraft to large transport ships. Turbulent boundary layers are also ubiquitous in the energy sector, from gas turbine engines to large-scale wind farms. Even with such wide-ranging applicability, our current understanding of the fundamental physics of wall-bounded turbulence leaves much to be desired. Key topics include the identification and role of coherent structures and the development of efficient flow control and drag reduction technologies, as well as understanding how turbulent boundary layers respond to high-speed effects. These issues were the focus of six projects in the Analysis of Turbulent Boundary Layers group.

Coherent structures in atmospheric boundary layers were the topic of Momen *et al.*, who studied the effect of rotation on hurricane boundary layers. They utilized a novel scheme to simulate the hurricane boundary layer in a subregion so as to avoid the need to include the entire storm in the simulation domain. This allowed for turbulence-resolving large-eddy simulations to be run over a range of parameter values. The team analyzed the effects of physical parameters such as distance from the center of the storm as well as numerical parameters such as subgrid model coefficients. Meanwhile, Elnahas *et al.* studied coherent structures in aerodynamic boundary layers. They identified and tracked structures through the late stages of transition to observe the similarities and differences between the transitional and fully turbulent regions. In this work, structures are identified as coherent regions of space belonging to the same quadrant via quadrant analysis. Quadrant analysis assigns each point in space into one of four quadrants based on the sign of streamwise (u') and wall-normal (v') velocity fluctuations, allowing for the identification of coherent ejections and sweeps. They identified that the geometrical properties of strong and attached sweeps and ejections are the same between the fully developed stages of turbulence and the late stages of transition.

Yang *et al.* proposed a transformation for boundary layers with imposed streamwise pressure gradients. Inspired by variable property transformations used for high-speed boundary layers, this work nondimensionalizes the streamwise velocity and wall-normal coordinate using local velocity and length scales that vary with wall-normal distance. The transformation successfully collapses a wide range of velocity profiles into a single law of the wall profile.

On the topic of flow control and drag reduction, Shariar *et al.* developed a fully coupled computational framework for fluid/structure interaction to study the potential of passive flow control and drag reduction via the design of compliant surfaces. Taking inspiration from dolphin skin, an anisotropic subsurface structure is studied in their work. One key step in their work is the homogenization of the complex subsurface material structure to simplify the computational task. Due to the high cost of direct simulation with fluid/structure interaction, resolvent analysis is used to identify regions of interest in the overwhelmingly large parameter space for this problem.

At high Mach numbers, aerodynamic heating decreases the mass density and increases the viscosity within boundary layers. The net result is lower skin friction coefficients and Stanton numbers as the Mach number increases, but the wall temperature boundary condition also plays an important role. Kianfar *et al.* has extended the Angular Momentum Integral (AMI) equation to compressible flows to quantify how changes to the flow within turbulent boundary layers at high Mach number lead to the observed changes in skin friction and surface heat flux, providing a fundamental connection between high-speed turbulent boundary layer physics and engineering quantities of interest. When the freestream enthalpy is high enough, even more physical phenomena come into play. Di Renzo *et al.* elucidate the impact of the vibrational excitation of gas molecules on turbulent boundary layers. In this study, a canonical compression ramp geometry is chosen to characterize high-enthalpy effects on shock-boundary-layer interactions. In particular, it is shown that vibrational excitation can have significant effects on the heating and structural loads relevant to hypersonic vehicle design.

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