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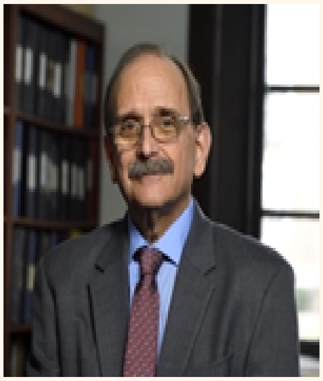
On the Interaction of Turbulent Boundary Layers with Compliant Surfaces



Joseph Katz

William F. Ward Sr. Distinguished Professor

John Hopkins University

ABSTRACT:

Interactions of a compliant wall with boundary layers have been investigated by simultaneously measuring the time-resolved, three-dimensional flow field and the two-dimensional surface deformation at friction Reynolds numbers varying between 2,300 to 9,000. The optical setup integrates high speed tomographic PIV/PTV for measuring the flow with Mach-Zehnder interferometry for mapping the deformation. The time-resolved 3D pressure field is calculated by spatially integrating the material acceleration. The process involves interpolation of the unstructured PTV data to a regular grid using a constraint-cost minimization code that forces the velocity field to be divergence free and the material acceleration, curl free. Integration of the acceleration is performed using a virtual boundary, parallel-line, omni-directional algorithm. Early experiments have involved stiff compliant walls with deformation amplitudes too small to affect the flow, resulting in one-way coupling between the flow and deformation. Subsequent experiments have been performed using softer material, resulting in two-way coupling, including momentum deficit in the inner part of the boundary layer, and a substantial increase in turbulence level. Combining data obtained from several references, trends of the deformation amplitude scaled by the compliant wall thickness collapse when plotted vs. pressure fluctuations scaled by the compliant material shear modulus. The deformation wave speed varies between 53% to 80% of the free stream velocity (53% in recent data), and the preferred wavelength is about three times the wall thickness, the latter being consistent with theoretical models. Conditional averaging and correlations reveal the characteristic 3D flow structure that affect the wall deformation, e.g., a spanwise vortex with a laterally inward flow above a surface bump inducing a sweeping diverging flow above a dimple located downstream of it. Adopting insight derived from atmospheric wind-wave interactions, the pressure-deformation correlation peak at the ‘critical layer’, where the mean flow speed is equal to the surface wave speed. The critical layer is located within the log layer, increasing in elevation with increasing Reynolds number. For the entire region below this layer, wavenumber-frequency spectra of pressure and vertical velocity fluctuations indicate that the turbulence is phase locked and travel with the deformation even for deformation amplitudes much smaller than a wall unit. In contrast, above the critical layer, the turbulence is advected at the local mean streamwise velocity, and its coherence with the deformation decays rapidly. These findings indicate that the height of the zone dominated by flow-deformation interactions is determined by the surface wave speed.

BIOGRAPHY:

Joseph Katz received his B.S. degree from Tel Aviv University, and his M.S. and Ph.D. from California Institute of Technology, all in mechanical engineering. He is the William F. Ward Sr. Distinguished Professor of Engineering, and the director and co-founder of the Center for Environmental and Applied Fluid Mechanics at Johns Hopkins University. He is a Member of the National Academy of Engineering, as well as a Fellow of the American Society of Mechanical Engineers (ASME), the American Physical Society, and American society of Thermal and Fluids Engineering. He has served as the Editor of the Journal of Fluids Engineering, and as the Chair of the board of journal Editors of ASME. He has co-authored more than 430 journal and conference papers. Dr. Katz research extends over several fields, with a common theme involving experimental fluid mechanics, and development of optical and ultrasonic diagnostics techniques for laboratory and field applications. His group has studied laboratory and oceanic boundary layers, turbomachinery flows, flow-structure interactions, cerebral and cardiac vascular flows, plankton swimming, as well as cavitation, bubble, and droplet dynamics, the latter focusing on interfacial phenomena associated with oil spills.