Abstract

In-depth analysis of the coupled behavior of the boundary layer and flexible structure is vital for flow problems involving moving or deforming bodies. The fluid-structure interactions (FSI) are highly nonlinear and complex. The presence of thermal interactions further complicates the system at high-speed flows. The aero-thermo-elastic analysis explains the complex interplay between aerodynamic forces, thermal load, and restoring elastic energy. In addition to characterizing the aero-thermo-elastic interaction, this study aims to develop and improve the methods for fluid-thermal-structure interaction (FTSI) simulation. The fully coupled FTSI technique is formulated by a partitioned coupling approach, combining a finite element structural solver with a finite-difference flow solver. A high-order sharp interface immersed boundary method is implemented to represent the moving and deforming solid body. Advanced capabilities and methods like inflow turbulence generation, parallel communication between the solvers, shock generation, implicit coupling, thermal coupling algorithm, etc. have been added to the solvers to simulate complex flow problems. The solvers and coupling algorithm have been extensively validated for several complex and canonical flow problems.

Initially, the FTSI between the shockwave and laminar boundary layer (SBLI) over a flexible surface with different thermal conditions is studied. The FSI framework couples a finite element structural model with a high-order sharp interface immersed boundary flow solver. The flow is characterized by an oblique shock on a laminar boundary layer over a compliant panel with cavity pressure. The influence of different flow and structural properties on the decay rate, amplitude, and frequency of the panel oscillation has been quantified. The reduced extent of the separation bubble in colder walls results in a stronger shear layer. This suggests that a colder wall may lead to a higher adverse pressure gradient. The difference between the average surface pressure at maximum and minimum flexibility increases as the wall temperature drops, hence the effect of panel oscillation is most amplified at the lowest wall temperature. For thermally coupled conditions, the thermal dependency of the structural properties significantly impacts the dynamics of the panel oscillations. The study revealed that a stable, decaying sinusoidal oscillation transformed into a limit-cycle oscillation as the panel stiffness is affected by a reduced wall temperature. During the sustained oscillation, a mode switch was observed between the first and second modes of deformation of the panel.

Building upon the findings in laminar conditions, this study explores how turbulence affects FTSI in SBLI over a flexible panel. Temperature changes alter the material's stiffness, damping characteristics, and behavior, causing spatiotemporal variations in the system. To better characterize these complex interactions and panel deformation, the primary mode shapes of the panel oscillations are identified through proper orthogonal decomposition (POD), a technique to extract dominant patterns in data. POD revealed that a colder wall could lead to more symmetric spatial modes. The first natural mode shape of a clamped-clamped panel is the most energetic for the adiabatic wall. Interestingly, the second natural mode shape becomes the most energetic for the colder wall. To address the longer timescales of thermal interactions, attempts have been made to create a reduced-order representation of the turbulent flow. Employing a data-driven resolvent analysis, the forcing and response relationship is identified for the turbulent SBLI. Furthermore, to explore the effect of an anisotropic flexible surface, simulations have been conducted for turbulent channel flow over a composite and multi-material compliant surface.

In a separate study, a canonical vortex-dominated flow problem, cross-flow over an axisymmetric body, is explored while implementing the novel idea of the force/pressure partitioning method. This flow problem is particularly interesting due to its association with vortex asymmetry, instability, and breakdown. In this flow problem, the vortices play the most important role in the generation of aerodynamic body forces. Direct numerical simulation is used to solve the flow over the axisymmetric cone for a wide range of angles of attack. For higher accuracy and resolution near the body, an immersed boundary method with pseudo-body-conformal grids is employed. It is found that two near-wake stable primary vortices form in the separated shear layer, which induces reverse flow in the wake and initiates another two strong secondary vortical structures on the surface. For a higher angle of attack, the primary vortices become asymmetric and hence induce side forces. The contribution of different flow features in the wake of axisymmetric elongated bodies has been investigated in this study by relating the localized surface pressure to coherent flow structures. Using an extension of the force portioning approach, we study the role of major vortical structures on the force generation and pressure distribution on the cone surface and find the asymmetry's origin.