ABSTRACT

Vortex asymmetry at high angles of incidence has been extensively investigated due to its significant impact on aircraft trajectory, maneuverability, and performance. Slender axisymmetric bodies at high angles of incidence produce asymmetric flowfields dominated by crossflow shear layer separation and forebody vortex dynamics. These flow asymmetries result in large uncontrolled aerodynamic forces that can alter the stability and control performance of flight vehicles, particularly in the subsonic to transonic Mach number regime. In particular, compressibility alters pressure distribution and shear layer development, leading to significant variations in aerodynamic forces and moments that impact vehicle stability, control, and structural integrity. Despite decades of research, the fundamental flow physics regarding the effects of compressibility on vortex asymmetry remains relatively elusive, especially due to the coupling of Mach number and Reynolds number effects.

This experimental study aims to investigate the role of compressibility while decoupling Reynolds number and Mach number effects on crossflow separation and vortex asymmetry. The test configurations include an 8° semi-apex angle conical forebody with a slenderness ratio of 3.5 and a cone cylinder model with a slenderness ratio of 6, respectively. Measurements include a combination of force measurements, surface pressure measurements, particle image velocimetry (PIV), and shadowgraph visualization. Experiments were conducted at varying Reynolds numbers and velocities to achieve a controlled decoupling of viscosity and compressibility effects on vortex behavior.

Results show that vortex asymmetry and associated side forces depend on Reynolds number in the low subsonic regime, with peak asymmetry in both the laminar and turbulent regimes and a minimum in the transitional range. Flow visualization confirms that the asymmetry mechanism varies with the boundary layer state, transitioning from absolute instability in the laminar regime to convective instability in the turbulent regime.

The results at subsonic speeds show that, with an increase in the angle of incidence, counter-rotating vortices develop asymmetrically over the forebody, resulting in side forces. Unlike previous literature, the variation of the maximum side force coefficient with Mach number is non-monotonic. At high supersonic speeds, both side force and vortex strength diminish significantly regardless of an increase in the angle of attack. This study demonstrates the need to decouple the Mach and Reynolds number effects to determine the nature and magnitude of vortex asymmetry. Current

findings strongly suggest that compressibility has a crucial effect on cross-flow shear layer development that determines the overall flow asymmetry and the strength of side forces generated at high angles of incidence. These findings reinforce and extend prior work by Lamont, Keener, and Hunt[19, 24, 15], providing new insight into the relation between viscous and compressible effects in asymmetric flow separation. These results directly relate to the design and control of maneuvering flight vehicles, missiles, and smart projectiles operating in complex aerodynamic environments. This experimental database is very valuable for the validation of numerical tools being developed by another researcher at the FAMU-FSU College of Engineering.