Abstract

When two slender bodies are closely spaced within a supersonic freestream, substantial aerodynamic interference precipitates between the bodies. The bow-shock wave and forebody expansion field produced by an adjacent body (the disturbance generator) impinge onto the body of interest (the disturbance receiver), which modifies its surface pressure distribution, effectively altering its nominal centre of pressure and overall aerodynamic behaviour. The three-dimensional, curved bow-shock interactions have increased complexity due to the multiple shock reflections, shock wave diffraction and viscous-shock interactions manifesting with the receiver at incidence in the interference domain. This research aims to uncover and characterise the underlying flow physics that are generated in the disturbance flowfield for several multi-slender body configurations.

Parametric wind tunnel investigations were conducted on pairs of slender bodies with ogival, conical and hemispherical forebody profiles over a wide incidence range. Primary experimental data was collected using the surface oil flow visualisation technique, where a quantitative data extraction method was employed to measure the shock impingement location and diffraction path over the receiving body. Supporting schlieren images of the flowfield were captured through a standard z-type schlieren system. In addition, time-averaged numerical solutions of the Reynolds-averaged Navier-Stokes governing equations were conducted using a commercial flow solver. A custom, gradient-based adaptive mesh refinement algorithm was tailored into the package, providing fine resolution of the pressure waves in the flowfield. The high-fidelity computational predictions showed excellent agreement with the experimental data and was used to examine the vortex and shock wave dynamics produced by the interactions.

A high geometric dependence was observed across all interactions, where the magnitude and extent of impinging disturbances were bespoke to each configuration, making it challenging to extract overall trends. However, the interactions could be categorised under three general genres: The first were the primary windward interactions, where the receivers were negatively pitched relative to the generator bodies and the impinging disturbances made first contact with the receivers' windward surface. The second category had the receiver bodies at positive incidence in relation to the generators, where impinging disturbances impacted the bodies' leeward surface directly, and were designated as primary leeward interactions. The last category assessed the receiver bodies at angles of sideslip relative to the disturbance generators, where the disturbance bow-shocks impinged asymmetrically on the receivers. Under each of these categories, the mechanics of the interactions were observed to be predominantly similar.

Primary windward interactions: Characteristic to these interactions was the locally elevated windward surface pressure, which created favourable pressure gradients in the natural crossflow direction over the bodies. Disturbance shock wave diffraction over the bodies induced significant effects of compressibility onto the separated flow in the leeward region, producing body-vortices that were elongated, more elliptic and intensified in comparison to that produced by equivalent undisturbed bodies. Moreover, the receivers' body-vortices had a significant influence on the disturbance shock waves' transit into the leeward flow region, where the wave was tempered during passage through the vortices.

Primary leeward interactions: These configurations generated direct shock wave-leeward flow structure interactions where the inherent low pressure in the receivers' leeward region attracted the approaching waves, causing the bow-shocks to bulge out locally towards the bodies. The opposing natural crossflow over the receivers tempered the disturbance shock waves' transit into the windward region, generating complex three-dimensional shock wave geometries around the bodies. Moreover, the viscous-shock interactions caused severe distortions to the vortical structures disposed by the receiver bodies.

Interactions with the receiver bodies at angle of sideslip: Additional complexities were generated by these interactions due to the inherent three-dimensional flow asymmetry, where waves of unequal strengths diffracted over the windward and leeward surfaces of the receiving bodies. The windward portion of the diffracted wave caused substantial elevations in surface pressure and an enhanced crossflow condition over the bodies. The wave that diffracted over the leeward surface interacted progressively with the receivers' body-vortices, which caused an imbalance in the strength of the vortices disposed on either side of the bodies. The strong rotational velocity field of the vortices influenced the disturbance waves' transit over the leeward surface substantially, producing complex compression wave topologies in the receivers' leeward region.

In general, significant reorganisation of the receivers' near-surface flow topologies was observed across all three categories of interactions, the extent of which varied with incidence and the strength of impinging disturbances. It was also found that the inhomogeneous pressure field introduced by the disturbance shock waves caused significant modification to the receivers' incidence-induced body-vortices. In addition, the inhomogeneous velocity field of the receivers' body-vortex pair were observed to affect the disturbance waves' transit into the bodies' leeward region. Overall, studying the slender bodies orientated to produce 3D, curved bow-shock interactions revealed several fundamental mechanisms and flow physics in the flowfield, with rich phenomena manifesting in the interference domain.