Dynamic Stability Analysis using Free-Flight CFD

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1 Abstract

Blunt body probes are the primary design for atmospheric entry. The blunted capsule shape, while desirable for the decreased forebody heating, typically experiences dynamic instability at low supersonic and transonic flight. At moderate to low supersonic conditions, the unsteady wake begins to adversly interact with the vehicle in free-flight resulting in attitude oscillations which can grow in time and result in tumbling. Understanding vehicle dynamics is thus important when considering vehicle entry design and guidance navigation and control (GNC) considerations. Historically, dynamic stability has been carried out exclusively using experimental techniques. The wide range of experimental approaches provide reasonable coverage in Mach and dynamic pressure space for a given trajectory, however achieving flight similitude is often difficult or impossible.

Advancements in Computational Fluid Dynamics (CFD) techniques allow for dynamic motion of the vehicle surface during the simulation with either forced/prescribed motion or free motion in response to fluid forces. Several examples of CFD software with the ability to simulate fluid dynamics and vehicle motion are available in literature. The Free-Flight CFD (FF-CFD) capability developed by NASA Ames within the US3D flow solver has shown extensive validation and verification (VV) efforts from moderate to low supersonic flow across a range of vehicle architectures. The solver is able to simulate full rotational and translation motion resulting in full 6 degrees-of-freedom (DoF) motion. The validation and verification efforts the solver's ability to predict the motion of a ballistic range model as compared to experimental results.

Similar to other computational capabilities in literature, FF-CFD relied on heritage data reduction methodologies and processes for reducing dynamic data into aerodynamic coefficients intended for use in design and trajectory codes. These heritage approaches, initially developed with the assumptions (and restrictions) of ground test facilities, resulted in the significant culling of the full 6-DoF dynamic data set to discrete values which are then fit using an aerodynamic model. Recent development of simulation and data reduction methodologies has resulted in an improved approach to FF-CFD simulations of vehicle dynamics which leverage the control of dynamic constraints within a simulation set-up.

The presentation of this work will cover the constrained dynamic simulation approach for deriving dynamic coefficients for a Genesis capsule. The methodology will be outlined and a discussion of implications in motion restriction will be discussed. Finally, reconstructed vehicle trajectories using FF-CFD derived aerodynamic coefficients will be presented.