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Dynamic Stability of Atmospheric Entry Probes

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Introduction: Atmospheric entry capsules have been widely used in planetary exploration missions for more than four decades. Designed to survive the early hypersonic phases of the atmospheric entry, these blunt body vehicles often experience dynamic instability at low altitudes during transonic and subsonic flight regimes. Often, the unsteady flow field around and the near wake of these blunt geometries have been inferred as the likely mechanisms responsible for the onset of dynamic instability. However, the detailed quantification of the flow field and the manifestation thereof has been extremely scarce. Accordingly, the dynamic instability mechanism has not been completely understood. In the present study, the impact of the flow field on dynamic stability of a representative capsule shape at low speeds is investigated.

Dynamic instability: During the decent, an increase in the angle of attack envelope which corresponds to aerodynamic instability is not only linked to the steady aerodynamic characteristics and the inertial properties of the vehicle, but also to unsteady flow effects[2,3]. As for the main cause of instability, the unsteady flow effects such as; separation, re-attachment and wake unsteadiness are addressed[1]. During the descent trajectory of the vehicle, any changes in surface separation pattern have an important impact on the vehicle's behavior. Flow re-attachment or separation, even for a very short time period, results in a change of forces and moments through the modified surface pressure patterns. The unsteady wake has also been suggested as a contributing factor from various wind tunnel tests that revealed its influence of especially on the separated afterbody region[3].

Results: The aerodynamics of a representative entry capsule and its resulting dynamic and static stability characteristics are investigated in the present study. The most salient features of the three-dimensional unsteady flow field over a generic model are measured in the incompressible flow regime. The investigation of surface pressure variation on an oscillating capsule permitted quantitative assessment of the time lag effects and their impact on dynamical instability. The results reveal that, on a vehicle undergoing an oscillatory motion, the time lag between the surface pressure and the angular position is in the origin of the dynamically unstable behavior. Due to time lag effects, the pressure at a given angular position is not the same for stroke-up and stroke-down motions. This pressure difference is shown to be principally a function of the angular speed in attached flow regions and of the oscillation amplitude in separated flow regions. The additional forces and moments originated from the pressure hysteresis often act in the direction of motion, thereby creating a destabilizing effect. A mathematical model is built to reproduce this instability phenomenon based on the data collected. Although configuration dependent, the model allows to justify the trends observed by previous researchers on the effect of the center of gravity location and of the afterbody shape. The output of the present study can assist future development of dynamically more stable capsule geometries. Furthermore, it furnishes physical explanations to some experimental observations derived from ballistic and spin tunnel tests found the literature.

References:

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