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Review on Analysis & Modeling of Dynamic Stability Characteristics of Atmospheric Entry Vehicles

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Abstract

Atmospheric entry is a critical phase for a mission that seeks to return astronauts or scientific payloads back to Earth or explore the surface of a planet with an appreciable atmosphere. This paper presents a review of the comprehensive investigations on the dynamic stability of blunt body atmospheric entry vehicles. As blunt vehicle enters the planetary atmosphere, the aerodynamic moments acting upon it can result in unstable pitching motions and divergence of oscillation amplitude. Typically, these instabilities are found in the low or mid supersonic regime of the trajectory just prior to parachute deployment. A discussion on the underlying phenomena of dynamic stability is followed by effect of geometric and design parameters on stability. Numerical and analytical procedures used for modeling of the complex phenomena are also examined.

Keywords: Dynamic stability, Atmospheric Entry Vehicle, Pitch oscillations, Blunt body, Reentry Vehicle

Introduction

The Government of Pakistan has initiated the "Space Program 2040" with the aim to bring the benefits of the full spectrum of space technology to the people of Pakistan . Earlier space expeditions from Pakistan demonstrated lack-luster performance compared to other technologically advanced countries. In pursuance of Space Program 2040, Pakistan will launch five Geosynchronous Earth Orbiting (GEO) satellites and six Low Earth Orbiting (LEO) satellites between 2011 and 2040. The program intends to develop the military and space technologies and conduct experiments on fundamental sciences in space frontier. The ultimate realization of space programs is to send astronauts in space and subsequently retrieve them back on earth. For retrieval, Atmospheric Entry Vehicles (AEVs) are used around the globe. Therefore, the research pertaining to AEVs is also an integral part of space exploration program. In order to explore the solar system around us, AEVs are required to carry astronauts and scientific payload to outer space and return back to Earth. The mission profile of these vehicles requires a body that will exhibit high drag and low aerodynamic heating . The designs o AEVs have evolved over the years. Initially, in order to reduce the wave drag, configurations with extremely high fineness ratios (sleek designs) were developed. The objective was achieved by generation of oblique shock waves. However, at very high mach numbers, aerodynamic heating made these concepts unviable as the amount of heat generated from friction was passed directly to the body thereby resulting in undesirable temperature rise. Blunt shaped bodies generally meet these necessities.

Blunt body AEVs is an important research area. Its significance can be judged from the fact that all MARS expeditions intending to enter Martian atmosphere are blunt body entry vehicles. Once entered into Martian atmosphere, the blunt body initially reduces its velocity with the help of atmospheric resistance. Subsequently, in low supersonic regime, the drag chute is deployed to further decelerate it to subsonic speeds. In the final phase before touchdown/deployment of scientific payload, it jettisons its drag chute and becomes airborne with thrusters. Finally, the deployment of payload via sling on the Martian land culminates the mission of entry vehicle .

Blunt body AEVs are highly prone to aerodynamic instabilities. Specifically, a nonlinear dynamic phenomenon of limit-cycle oscillations is a feature of such vehicles that is of vital importance. The limit-cycle oscillations generally emerge in low or mid supersonic regime of the trajectory just prior to parachute deployment. The cause of these oscillations is generally attributed to the development of unsteady pressure forces on the aft body of the blunt body entry vehicle . The dynamic stability is a function of vehicle design, mission trajectory and environmental factors. The vehicle design considerations that govern the dynamic stability are overall geometry and mass distribution. From the mission trajectory perspective, the magnitude of oscillations should be less than 10^{o} where entry vehicle deploys the parachute [5]. All these design and mission considerations are fundamentally transferred to aerodynamics and stability coefficients graphs. These graphs depict the trend of stability coefficients as a function of kinematic variables (angle of attack, pitch rate etc.). The designers use these graphs to understand the dynamic behavior of atmospheric entry vehicles. However, the interactions are generally less understood and for that purpose, designers move towards experimental, numerical or analytical approaches.

In this paper, various efforts are consolidated systematically to decipher the dynamic stability characteristics of blunt body AEVs. The complex phenomenon accompanying dynamic response of blunt bodies is one of the main reasons of lack of knowledge in this area . Particular importance is given to the studies that explain the effect of vehicle design and mission environment parameters on dynamic stability. Vehicle design parameters include center of gravity positioning, aft body shape and roll rate. The mission environment parameters considered to be of critical nature are Reynolds number, Mach number and specific heat ratios. Modeling based techniques used to predict the dynamic response of this class of vehicles are also reviewed. It is anticipated that this literature will provide a comprehensive insight to the current knowledge of dynamic stability of blunt bodies.

The Dynamic Stability Phenomena

The flow structure accompanying a blunt body is discussed first, followed by the changes in this flow triggered from oscillations. In supersonic regime, a bow shock wave is formed upstream of the body. Downstream of the shockwave flow accelerates around the body. Flow adjacent to body shoulder experiences a large turning angle that results in the formation of expansion wave and flow separation. An unsteady low pressure recirculation region forms just aft the body. The core of wake is viscous and often subsonic whereas its external regions are inviscid and supersonic. The inclusion of flow perturbations and asymmetric vortex shedding triggers aft body 'lag' in fluid flow compared to fore body motion, making the phenomena even more complex [6].

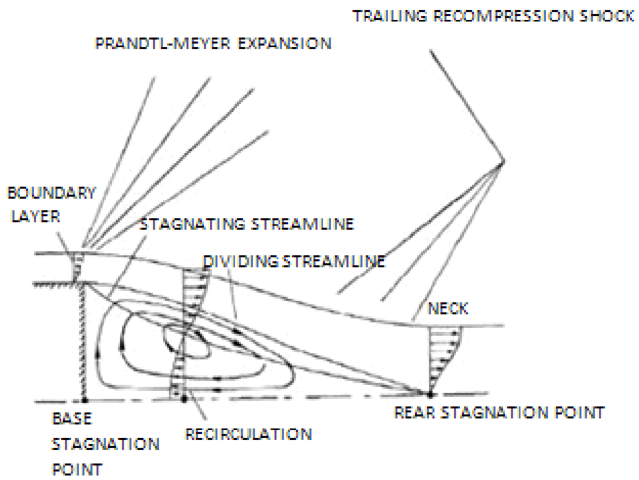


Fig. 1: Flow field behind blunt body [6]

Teramoto et. al. [7] numerically studied the dynamic instability phenomena accompanied with blunt bodies in detail. He studied the reentry capsule of Muses-C at Mach number 1.3 using free oscillation method.The findings from flow visualization are considered to be the most appropriate description of the phenomena to date. The density gradients in Fig. 2 show characteristic flow features around blunt bodies. A bow shockwave is observed ahead of body. Expansion waves and a wake region are evident in aft body regions. Initially, the body is in neutral position and the bow shock wave is also symmetric with reference to the body. In the aft region of the body, the wake is located slightly below the center line. However, the expansion wave formed is of non-symmetric nature. It can be concluded that the fore body region moves synchronously with the vehicle whereas the aft body region exhibits a delayed motion.

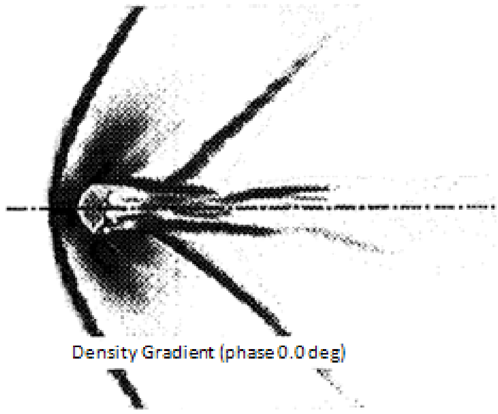


Fig. 2: Density gradient of blunt body [7]

Fig. 3 depicts the phenomenon that causes pitching moment hysteresis. Disturbances caused due to oscillations of vehicle are transported downstream by a finite convection velocity. This causes a delay in downstream oscillations. The motion of downstream shockwave is affected by these oscillations. A delay in shockwave formation also effectively delays motion inside recirculation region. The base pressure is controlled by this recirculation region. Consequently, the base pressure lags behind the fore body pressure. The net effect of this pressure lag is input of energy from the flow field into the pitching motion causing dynamic instability.

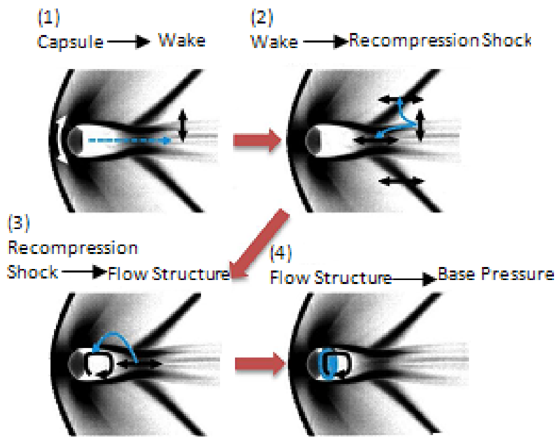


Fig. 3: Phenomena causing dynamic instability [7]

Effect of Geometric Parameters on Dynamic Stability

Effect of Centre of Gravity

Studying the effect of variation of Centre of Gravity (cg) location was among the preliminary studies carried out on dynamic stability. The study of Buell [8] indicated that in subsonic region dynamic stability was not much affected by change of cg location or angle of attack. Ericsson [9] studied the same configuration of Buell [8] in supersonic region at Mach number 2.5. Interestingly it was found that shifting cg axially forward, improved dynamic stability (decreases amplitude) and decreased range of angle of attack for unstable region. This is attributed to reduction in adverse effect of flow separation and reattachment caused due to more aft cg. Chapman and Hathaway [10] revealed the effect of angle of attack on cg. They found that at low angle of attack, forward cg improved damping whereas for high angle of attack, a more rearward cg was desirable. This data was obtained for a range of Mach numbers between 1.2 to 2.8.This effect can be seen from the reproduced results of Chapman and Hathaway [10] in Fig. 4.

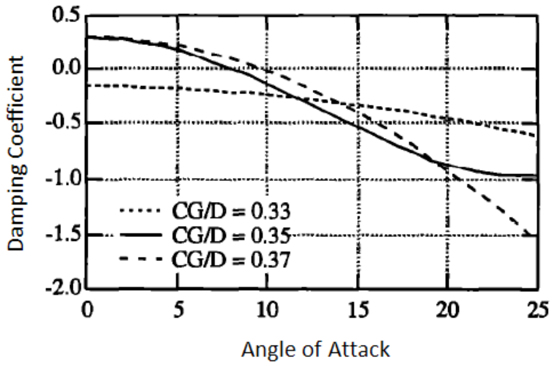


Fig. 4: Effect of angle of attack on cg [10]

Roll Rate

The effect of roll rate on damping is an area that has drawn moderate attention. Prislin studied the effect of various parameters on spinning descending vehicles. It was found that for a stable body increase in roll increases stability. However, for an unstable body increase in roll decreases stability. It must be noted that Prislin's study was conducted for the terminal regime. A need is therefore required to conduct a similar analysis for earlier phases of flight.

Effect of Aft Body:

Several studies [8, 9, 12] have been carried out to evaluate the effect of aft body on dynamic stability. All of the studies have come to the same conclusion that the presence of an aft body reduces damping at all mach numbers. For a parabolic body the effect is more pronounced at low mach numbers whereas effect is same for spherical body at all mach numbers. The effect of angle of attack on aftbody can be observed in Fig. 5. The spherical cone without any aft body is neutrally stable between angle of attack from -1 deg to +1 deg. As angle of attack approaches outside the limits, the reverse phenomena occurs. On the other hand, the body with a flare is unstable between -1 and +1 deg and stable otherwise.

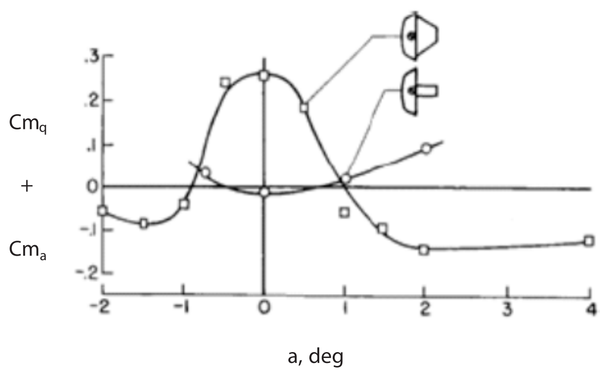


Fig. 5: Effect of aft body on damping with increasing angle of attack [8]

The effect of aft body flare is studied in detail by Fletcher [13, 14]. It is a geometry which becomes convergent after shoulder radius, reaches a minimum cross section and then increases in diameter, thus introducing a flare in the body. The effect of flare for a spherical cone was studied and it was found significantly reducing dynamic stability. The separated recirculation region aft the shoulder impinges with the expanding surface of the flare as seen from Fig. 6. This phenomenon involve interaction of unsteady pressure forces of recirculation region with shock structures created off the pinched region. Interestingly, it was found that, when the pinched region of spherical cone was moved axially forward to 54% of length, the effect of flare was removed and the flared body exhibited the same dynamic characteristics as the unflared body. The same configurations of spherical cones with flared body were tested in subsonic regime. The results found were strikingly different from supersonic tests. It was found that an unflared body was dynamically unstable. However, addition of flare made it stable. The more forward position of the pinched section was more stable as compared to a rearward position. The clear contrast in flare body characteristics in sub and supersonic regimes indicates the difference in flow structures of the two regimes and their subsequent effect on dynamic oscillations.

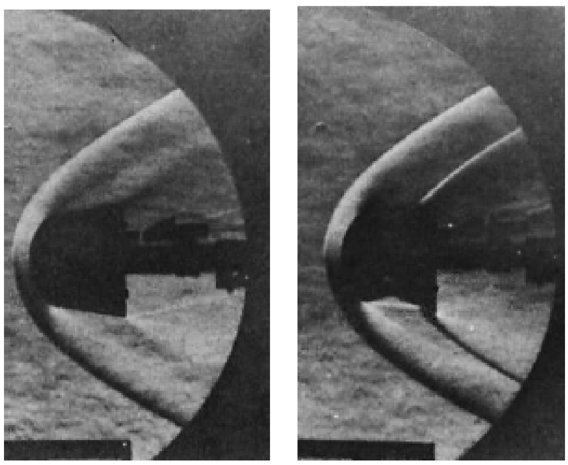


Fig. 6: Effect of aftbody flare on damping [14]

Effect of Environmental Parameters on Dynamic Stability

Numerous environmental parameters strongly affect the dynamic stability of blunt bodies. Specifically, Mach number, Reynolds number and specific heat ratio effects are considered in this study.

Mach Number

In the hypersonic regime the body remains stable or neutrally stable. As mach number reduces to supersonic regime the body becomes unstable with peak instabilities introduced from mach 3 to 1. In the transonic regime a second instability can be observed, these oscillations again damp out in subsonic region. The simulated angle-of-attack history from Mach 6 to transonic speeds by Smith [15] is reproduced in Fig. 7. Smith conducted study on a 70° conical capsule similar to previous Mars entry capsules without any flare. He simulated free flight behavior of capsule at cg 0.3 It can be seen that instabilities are introduced at mach 2.8 which continue to increase in amplitude.

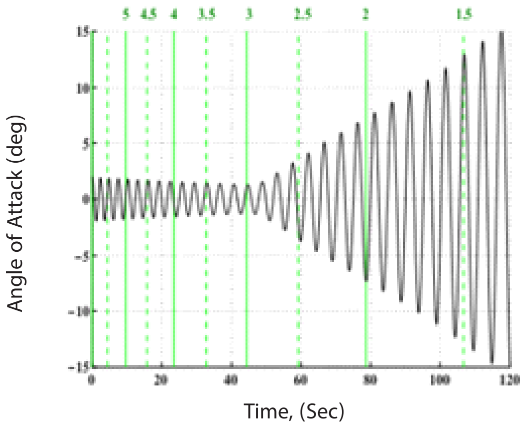


Fig. 7: Effect of Mach number on damping [15]

Reynolds Number

The effect of Reynolds number has been studied over the years for different configurations. However, explicit inconsistencies in results are reported. In some cases Reynolds number affects damping whereas in others it plays insignificant role. The results of two different studies are presented in Fig. 8 and Fig. 9. Fig. 8 represents the results of Owens who studied the Orion capsule at Mach 0.3 [16]. It shows a change in magnitude of damping with angle of attack and Reynolds number. The study also suggests that tests should be conducted above 5.0 x106 and not below 3.0 x106. On the contrary, results of Chapman [17] are presented in Fig. 9 that indicate a very little change in damping with Reynolds number. Chapman studied the Stardust capsule at nominal Mach number of 2. From these studies it can be assessed that Reynold's Number effect may be coupled with Mach number regime. Further study of this effect is however required to lead to any definitive conclusion.

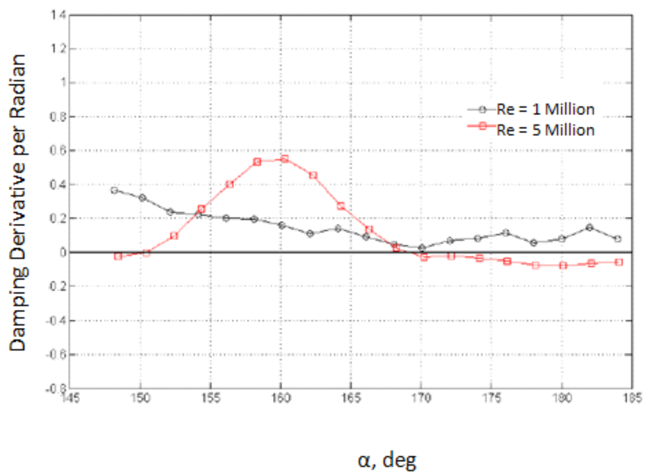


Fig. 8: Effect of Reynolds Number on damping [16]

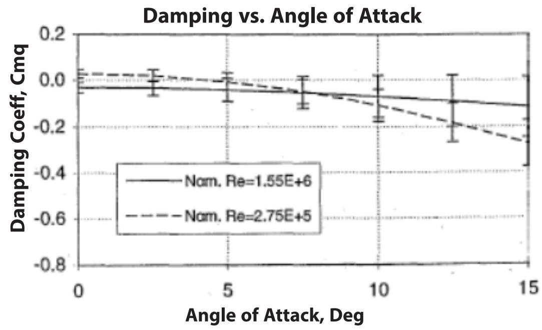


Fig. 9: Effect of Reynolds Number on damping [17]

Specific heat ratio

Chapman [18] revealed that the specific heat ratio of the medium can affect dynamic stability of the system. Krumins [19] measured the change in flow configuration and its subsequent effect on stability due to change in medium from air (γ= 1.4) to Tetrafluoromethane (CF4, γ = 1.12). The change in flow patterns is depicted in Fig. 10. Flow field for CF4 shows highly compressed flow in forward region with a high pressure base causing high drag. In air, flow separation is clearly visible. For the same mach numbers conical configurations were found to be unstable in CF4 and stable in air. Such effects were not observed for spherical configurations.

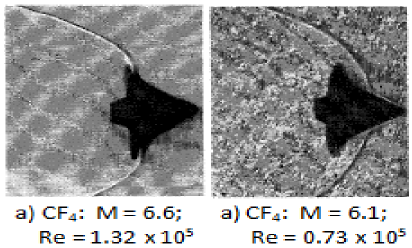


Fig. 10: Effect of medium change on flow field [19]

Modeling of Dynamic Stability Characteristics:

Semi-empirical Techniques

The fundamental Newtonian impact theory was initially used for hypersonic vehicle design. It assumes that change in normal component of velocity takes place on impingement with no change in tangential velocity component of particles that continue to move along surface of body [20]. The mathematical formulation of Newtonian flow model is based on small perturbation theory that is applicable only for slender bodies at small angles of attack. For blunted or round geometries it gives large errors because of extremely large flow deflection angles. To cater for curved particle trajectories in shock layer, a centrifugal pressure term was added by Busemann [21]. The method was called Busemann-Newtonian theory. This theory is however applicable to infinitesimally thin shock layers such that mach number approaches infinity and specific heat ratio approaches one.

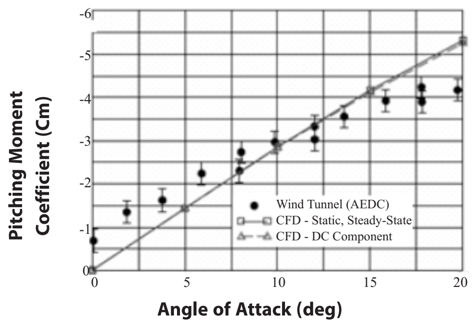
Actual hypersonic flights consist of shocks with finite thickness, and bow shocks determined by nose shape and drag coefficient. Under these conditions the Busemann-Newtonian theory is not applicable. Seif [22] modeled these effects in the semi empirical embedded Newtonian method. Originally, it was developed for steady flows and region downstream of shock was assumed to be non uniform rotational and inviscid. This method considers the effect of entropy layer aft of nose body in calculating pressure and velocity terms for embedded downstream body.

Ericsson [23] extended the embedded Newtonian concept to unsteady flow problem and determined the static and dynamic stability of flared body of revolution. Ericsson [24] further extended his study to remove the hypersonic mach number restriction and include the effect of mach number down to mach number of three. Tong and Hui [25] extended this method to give embedded Newtonian Busemann technique to cater for the limiting case of Newtonian theory. Hence it is concluded that several assumptions hamper the accurate analytical or empirical modeling of dynamic stability characteristics to-date.

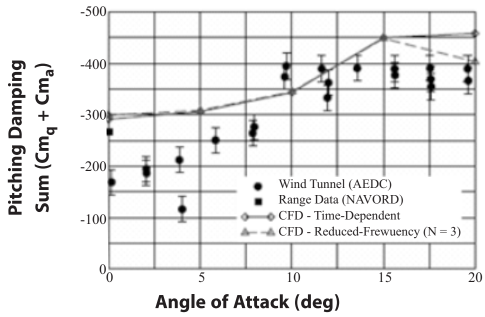
Computational Fluid Dynamics

Static stability derivatives are accurately estimated by Computational Fluid Dynamics (CFD) as they consist of a steady state simulation of a fixed geometry. Dynamic stability derivatives however require unsteady flow conditions to be simulated by a moving geometry. This is a complex phenomenon whose numerical solution can be computationally intensive. In the past, CFD of dynamic stability parameters involved calculating values at critical points and extrapolating results at other regions, simplification of geometry, or using a time dependent moving geometry simulation which is both time and computationally intensive.

Murman [26] introduced the reduced frequency approach. He proposed that instead of resolving for a continuum of frequencies (time dependent simulations) only a few frequencies of interest can be used to represent a forced motion. This method leads to a reasonably accurate solution with reduced computational effort. Initial validation was done using missile and aircraft configurations. A good agreement between experimental and simulated results was found as can be seen from Fig. 11. The variation of static and dynamic pitching moment coefficients with angle of attack are represented for the missile configuration at Mach 1.96. A good agreement is found between the graphed output from wind tunnel data, time dependent solution and reduced frequency method. The analysis discussed above uses the linear damping model. Further work is required in determining the response of reduced frequency method to nonlinear damping.



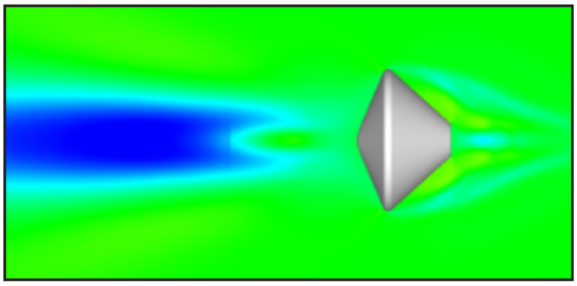
(a)



(b)

Fig. 11: (a) The variation of static pitching moment coefficients and (b) dynamic pitching moment coefficients with angle of attack [26]

Murmann [27] also carried out numerical analysis of blunt body re-entry vehicles. CFD of these configurations poses great difficulty due to flow separation and complex flow behavior aft of vehicle. CFD was used to calculate damping derivatives for both free and forced oscillations. Fig. 12 represents the sensitivity of drag and pitching moment to axial perturbations. The configuration analyzed is the MER capsule with cg= 0.27 at Mach 2.5. It is reported that drag is sensitive to changes ahead of body whereas pitching moment is sensitive to both fore and aft body flow changes.



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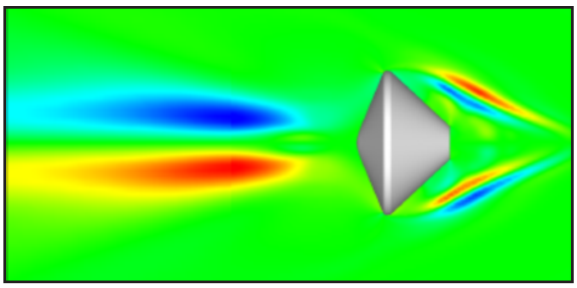
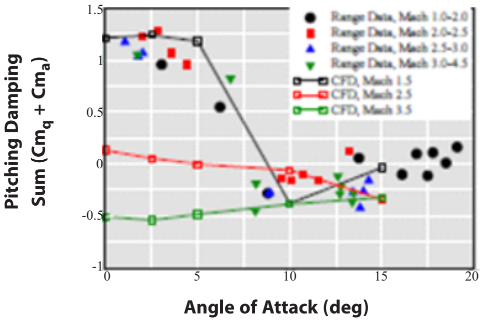


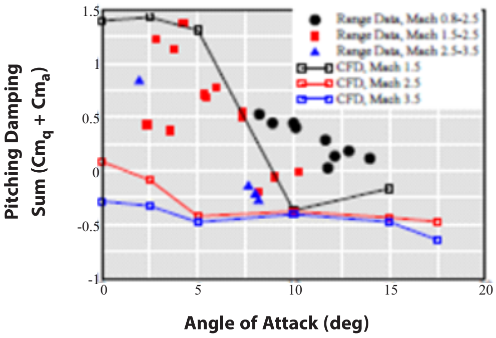
(b)

Fig. 12: Pressure contours for (a) static pitching moment (b) and axial perturbations [27]

The free oscillation CFD simulations compared with range data are shown in Fig. 13. The results show that CFD predicts greater damping at high mach numbers and lower angles of attack conditions.



(a)



(b)

Fig. 13: Comparison of range and CFD data for Genesis and MER vehicle [27]

One of the most recent works of Stern [28] suggest the use of CFD in the analysis of new entry vehicle shapes to meet future entry, descent and landing challenges. Stern performed both inviscid and viscous simulations of Mars Science Laboratory entry vehicle at Mach 3.5. The inviscid results predicted the static coefficients accurately whereas there was moderate agreement between experimental and numerical results for the dynamic coefficients. The viscous results showed a better agreement with experimental data as shown in Fig.14. The viscous simulations however required greater computational cost.

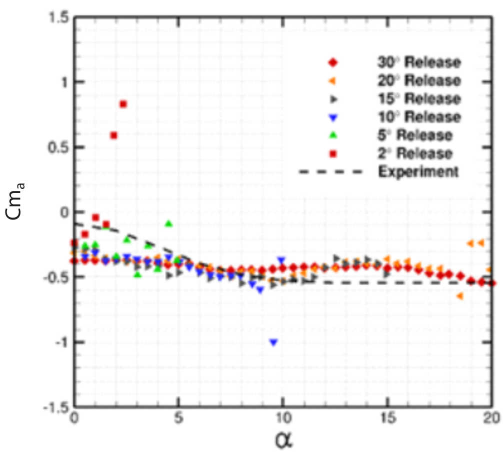


Fig. 14: Viscous results of pitch damping coefficient at Mach 3.5 [28]

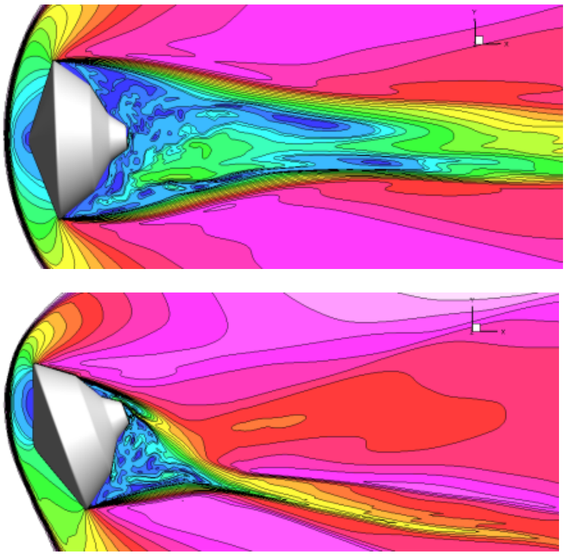


Fig. 15: Contours of Mach number at alpha 0 ° and 20° [28]

Conclusions

A brief discussion of the various contributions to dynamic stability phenomena in AEVs and its effecting parameters is presented. A considerable literature on experimental and numerical analysis of geometric considerations is available. However, lesser information is available on parametric studies of the same. Also it is found that some geometric effects have been studied more than others such as body configuration and centre of gravity have been studied more as compared to shoulder radius. Dependence of parameters on more than one factor creates difficulties in studying their independent effects. Among the design parameters, further investigation of effect of Reynolds number is also required as no conclusive results have been deduced. Numerical predictions by semi-empirical techniques have faced severe limitations due to the high complexity of the phenomena. CFD techniques pose a good possibility of numerical analysis provided the system is accurately modeled. The empirical and numerical efforts summarized, however, indicate that much effort is still needed to understand this complex phenomenon.

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