Roll Damping Analysis of Crew Escape Vehicle with Grid Fins at Subsonic and Transonic Mach Numbers

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ABSTRACT

Crew Escape Vehicle (CEV) is a man rated vehicle, which is used to eject the crew module from main rocket in an emergency situation so that the crew can be saved. Grid fins are employed in this vehicle for aerodynamic stabilization. Aerodynamic characterization is quite crucial for mission simulation and studies. Static and dynamic aerodynamic coefficients govern aerodynamic behavior among which roll damping derivative represents aerodynamic damping due to roll motion. Roll damping derivatives are obtained from wind tunnel tests for range of Mach numbers but sparse data is available due to cost overhead hence CFD has been employed for same. Forced oscillation technique using CFD++ software has been validated for Basic Finner configuration and same has been applied for CEV in current studies. Roll damping derivative are obtained for CEV and compared with wind tunnel results. Current studies have been carried out for subsonic and transonic Mach number but can be extended to supersonic Mach number.

Keywords: *Crew Escape Vehicle, Wind tunnel, Roll damping, Subsonic, Transonic, CFD*

1. INTRODUCTION

Stability characteristics of a launch vehicle depend on factors like angle of attack, Mach number, body rate, etc. Determining the stability of a Crew Escape Vehicle (CEV) [1] itself is a challenging process due to its complex flow field associated with the complex geometry. CEV is designed to take away crew module from the launch vehicle during the failure at the launch pad or at high altitude. CEV ejects the crew module into the intended trajectory such that the module is taken far away from the accident site. This study is done for various Mach Numbers at subsonic and transonic flow regimes. The static stability parameters can be estimated from either wind tunnel or CFD methods, whereas the dynamic stability parameters have been estimated from wind tunnel testing, in general. Owing to the advancement in CFD solvers, now CFD can be efficiently applied to determine the damping derivatives and hence been used in current study. Forced oscillation technique [2] has been employed in CFD framework to obtain roll damping derivative for CEV. The method has been also applied on Basic Finner [3] configuration and compared with wind tunnel test data for validation.

2. LITERATURE REVIEW

C Babu et al., 2018 [1] studied aerodynamic characteristics of crew escape vehicle with grid fin at subsonic to low supersonic Mach numbers. This study gives basic understanding about the nature of the vehicle in various Mach numbers. Also this study focuses on the contribution of the grid fins on the normal force. From the results it could be observed that there is an increase in normal force while approaching sonic speed. Solver details for the current study are based on this research.

James De Spirito and Karen R Heavey, 2004 [2] undertook CFD computations of Magnus Moment and Roll Damping Moment of a Spinning Projectile. The primary objective of the study was to determine the parameters necessary for estimating the Magnus moments and roll damping on a spin-

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stabilized projectile. This study gives us information that steady state CFD with appropriated source terms is adequate to calculate roll damping. This paper suggests k-ε turbulence model for better convergence of aerodynamic characteristics in steady simulation.

H Sundaramurthy, 2012 [3] carried out wind tunnel testing in NAL for Basic Finner configuration at subsonic and transonic regime for roll damping measurements. The test was conducted for various roll rates and a linear plot was obtained between rolling moment and the roll rate. The results of the study suggested that C_{lp} is invariant with roll rate. This research serves us with the data for the validation of the current methodology with the Basic Finner.

3. Problem Formulation

Equations of motion for a flight are derived from a body-fixed coordinate system. The nose of the vehicle is chosen for the ease of calculation. Right-handed coordinate system is used as the convention.

As shown in Figure. 1 the coordinates are defined below

x axis is in the symmetry plane pointed inward of the vehicle from nose to base.

y axis is perpendicular to the x axis and points upward.

z axis is mutually perpendicular to x-axis and y-axis.

Rolling is a rotation of the body about the x-axis and the counter-clock wise rotation is assumed to be positive. A system is said to be stable when the disturbance encountered is damped by the vehicle. Damping is the resistance offered by the aerodynamics of the vehicle or any other active mechanisms to a disturbance. Roll damping is the force caused on the lifting surface of the flight to counter the rolling moment produced during the flight. Roll damping derivative is a function of the roll rate.

$$C_{l_p} = \frac{dC_l}{dp} \quad \text{.....(1)}$$

$$p = \frac{\bar{p}d}{2V} \quad \text{......(2)}$$

4. Methodology

4.1 Forced Oscillation Technique

Forced oscillation technique involves forced movement of rigid body under freestream flow which results in transient aerodynamic coefficients. The coefficient history is a function of static and dynamic aerodynamic coefficient and mathematical procedure used to derive same is explained in CFD++ manual [4]. For roll damping computation the body is forced to rotate about x-axis, using coordinate frame rotation. In this mode the momentum equations are augmented with a source term to account for the rotating frame of reference [4]. This allows undertaking this roll simulation using steady state simulation reducing computation burden without compromising the accuracy and same is also highlighted in literature [2]. The roll damping derivative is defined below in Equation 3

$$C_{l_p} = \frac{C_{l,2} - C_{l,1}}{p_2 - p_1} \quad \text{.....(3)}$$

where 1,2 represents the two different states.

The above equation is further simplified by assuming that rolling moment is zero for zero roll rate.

$$C_{l_p} = \frac{C_l}{p} \quad \text{.....(4)}$$

If the roll is not linear then a rate dependent or a local definition like Equation 3 should be used for estimating the roll damping of the system.

4.2 *Computational Approach*

4.2.1 *Configuration Used For CFD Simulation*

The configuration used in the study consists of a nosecone followed by a cylinder, flare and large cylinder within which the crew module is placed. Grid fins are placed at the aft of the CES to provide longitudinal stability. Internal design of the grid fins is lattice structure with blunted wedge as leading edge as shown in Figure. 1. Total vehicle length is of 3.9 times of larger cylinder diameter (D), the nosecone angle is 20° and flare angle is 31°. The arrangement of the grid fin is shown in Figure. 1 [1]

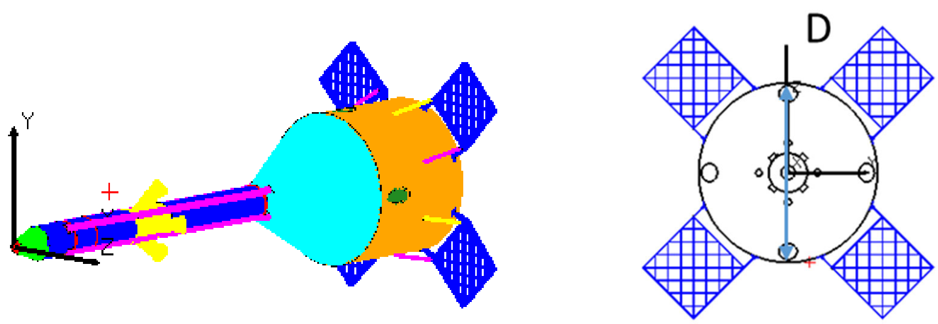

Figure 1: Configuration used for CFD simulation and the grid fins[1].

4.2.2 *Grid And Solver Details*

ICEM CFD is the commercial software used to generate the computational grid for CEV which is detailed in the study [1]. Volume mesh is generated around with surface triangulation. Mesh is resolved to solve the boundary layer flow by extruding the triangular prism from the wall. Farfield domains and the study configuration are shown with their respective boundary conditions in Figure. 2.

The domain of the control volume is 25D in all directions. In the entire volume there are 15.5million cells which include the 3.5 million near the wall and 12 million tetrahedral. CFD++ software is used to simulate the flow conditions. Compressible Perfect Gas solver with Realizable k-ε [2] turbulence model is utilized to solve the turbulence.

Grid motion/rotation along the X axis is invoked in the steady state solution to obtain the roll damping. The rate of rotation is kept same as that used in the wind tunnel tests. The input rate is referred from the available wind tunnel data.

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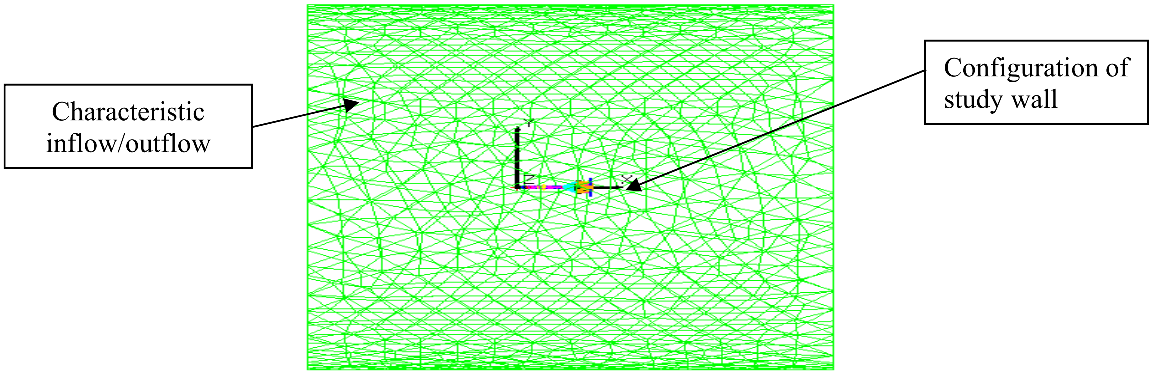

Figure 2: View of computational domain and boundary conditions [1]

4.2.3 *VALIDATION*

In general practice a simple model is chosen to validate a new method. This model is a calibration model. It is found that Basic Finner is found to be a widely accepted calibration model by the Supersonic Tunnel Association and AGARD [3]. These models were extensively tested on wind tunnels for various Mach numbers. Hence the Basic Finner configuration is used for validating our current analysis. Configuration of the Basic Finner consists of four rectangular fins on a cone body with the L/D of 10 as shown in Figures. 3 and 4.

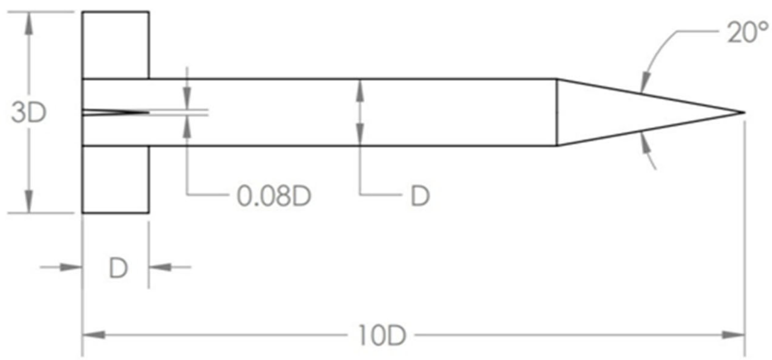

Figure 3: 2-dimensional view of the Basic Finner [3]

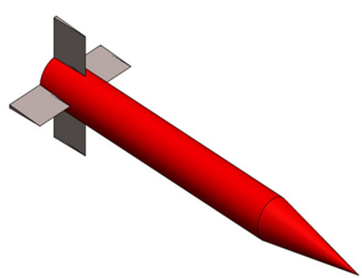

Figure 4: 3-Dimensional view of the model used for validation

Pointwise software has been used for generating mesh for Basic Finner. Volume mesh is generated with quad dominated surface and mesh is resolved to the boundary layer. Spherical domain of diameter 18.0 is used. The entire volume contains 19.47 million cells with 0.16 million cells surface mesh. The view of the domain and the grid are shown in Figures 5 and 6.

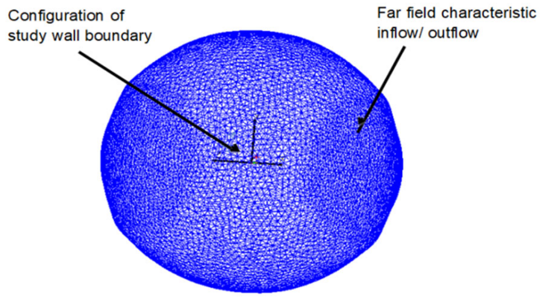

Figure 5: View of computational domain and boundary conditions

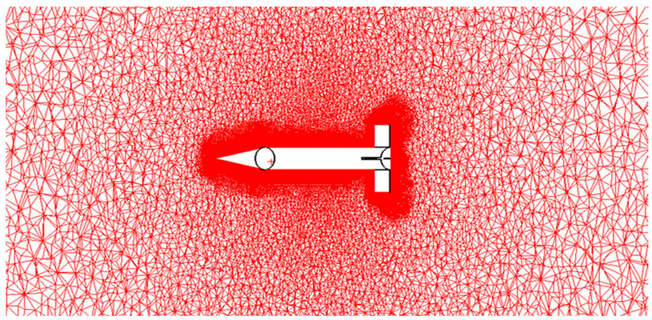

Figure 6: Grid in symmetry plane

The same solver setting is used as the above for Mach Numbers 0.5, 0.7 and 0.8 with zero incidence angles.

5. Wind Tunnel Testing

Measurement of C_{lp} through experiments requires a special purpose roll damping rig which was developed and validated during by NAL [3]. This rig employs the steady roll technique in which the model is rotated at a series of constant roll rates using a motor and the measurements of rolling moment on the model and its roll rate are made. The model is mounted on a single component low capacity rolling moment balance fixed at the upstream end of the sting, which in turn is supported on a pair of ball bearings. Figure. 7 shows the Basic Finner in the wind tunnel. Tests have been carried out in the wind tunnel for the series of subsonic and transonic Mach numbers. The same conditions are used for CFD simulations.

Figure 7: Basic Finner model in wind tunnel

6. RESULTS

6.1 *VALIDATION USING BASIC FINNER*

Forced oscillation technique is validated for Basic Finner for Mach Numbers 0.5, 0.7 and 0.8. Reference frame is rolled at the rate of 103 rad/s with Θ = 0° for all Mach number as per the literature. As shown in Figure. 8, the results compare within 5% with the literature data across all Mach Numbers. These results validate the method and hence the same technique is employed for CEV.

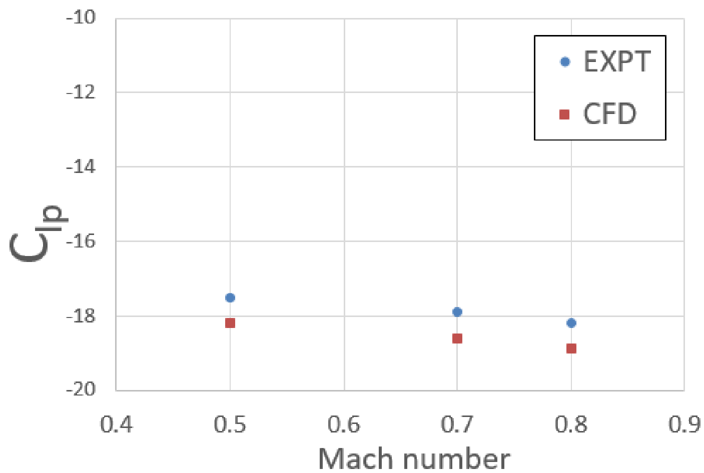

Figure 8: Comparison between computational and experimental results

6.2 *CEV CONFIGURATION*

Steady state simulation is carried out for 1000 iterations and then steady roll simulation is carried out for further 2000 iterations. Roll damping analysis is carried out at Mach numbers of 0.49, 0.71 and 0.8 for CEV configuration at angle of attack of 0° and -5°. The residual of mass, momentum, energy, turbulent kinetic energy and turbulent dissipation are shown in Figure. 9 at M = 0.71, the residual falls below 10^{-3}. Figure. 10 shows the convergence of normal force at M = 0.49, Θ = 0°.

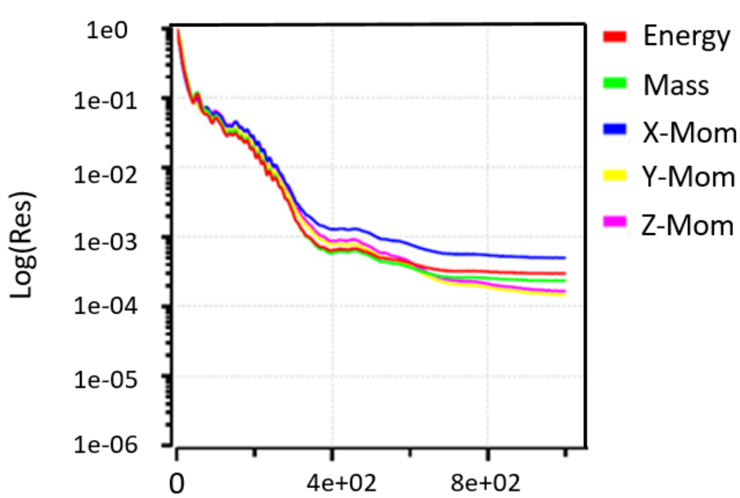

Figure 9: Convergence history for steady state at M=0.71 Θ = 0° for CEV

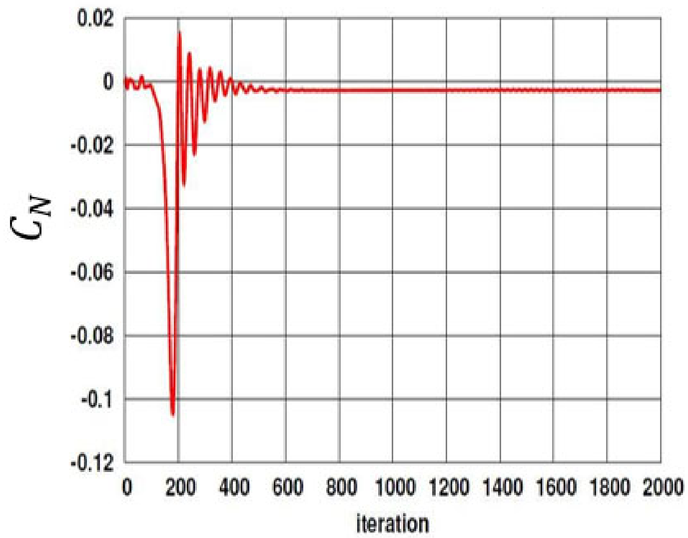

Figure 10: Convergence history of Normal force at M=0.49 Θ = 0˚ for CEV

The angle of attack of 0° and -5° are considered for the simulations. Figure. 11 shows the Mach palette at M=0.8 & Θ= -5˚ for the CEV in steady roll simulation. Expansion of flow at cone-cylinder junction leads to increase in Mach number which can be seen in palette. Also expansion region is visible at the nozzle cowlings. Large base flow is formed at the end due to aft body large diameter. Grid fin cells form a convergent-divergent section, resulting in acceleration of flow through the grid fins. Thus even though free stream Mach number is low transonic. the local Mach number through the pockets of the grid fins will tend to supersonic which is depicted in Figure. 11. Variation of the roll damping data with the Mach number and angle of attack along with its comparison with wind tunnel are shown in the Figure. 12. From the results it is evident that CFD data has a better match with wind tunnel data for angle of attack -5° and for angle of attack 0° there is a reasonable match across Mach numbers except 0.8. CEV comparison with wind tunnel data is not as good as Basic Finner validation case which is attributed to the lower value of loads for lattice grid fin as compared to planar fin. Also the grid fin flow resolution is being investigated to understand the sensitivity to modelling and mesh.

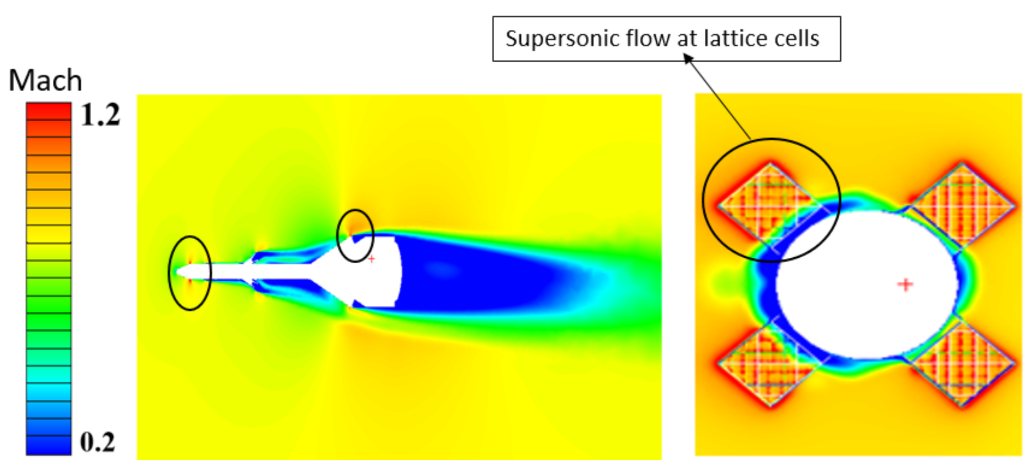

Figure 11: Mach Palette in steady roll case M=0.8 &Θ= -5˚for CEV

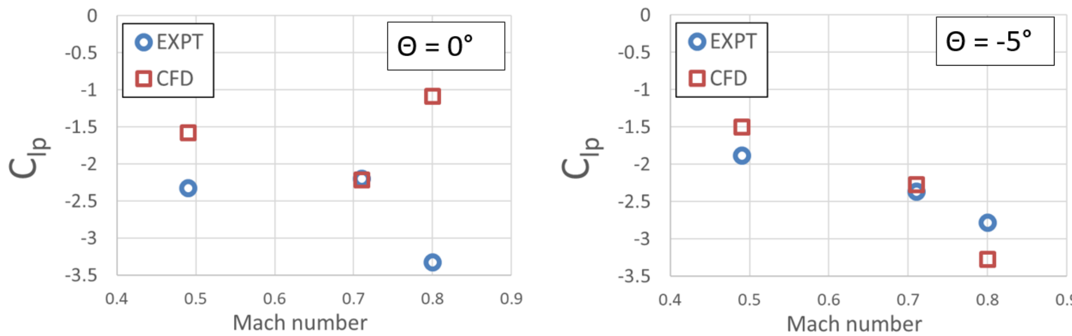

Figure 12: C_{lp} variation with Mach number at Θ=0°&-5° for CEV

7. CONCLUSIONS

Roll damping derivative of Crew Escape Vehicle (CEV) is carried out using forced oscillation technique employing coordinate frame rotation source term in CFD++ framework. The method is validated using Basic Finner model against NAL wind tunnel data. Simulations are carried out for the Mach numbers of M=0.5, 0.7 and 0.8. The results compare within 5% with the literature data across all Mach Numbers. Roll damping coefficient of a CEV is computed using the same methodology as in Basic Finner for Mach numbers of 0.49, 0.71 and 0.8 for Θ= 0° & -5°. From the results it is evident that CFD data has a better match with wind tunnel data for angle of attack -5° and for angle of attack 0° there is a good match across Mach numbers except 0.8. Grid fins have a major contribution to the roll damping characteristics of the vehicle. Flow resolution in and around grid fins is identified as major reason of mismatch which will be addressed in future studies.

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NOMENCLATURE

C_p	=	Coefficient of Pressure	
C_l	=	Coefficient of rolling moments	
C_{lp}	=	Roll damping coefficient	
C_N	=	Normal Force coefficient	
d	=	Base diameter of the reference vehicle	(m)
L	=	Length of the reference vehicle	(m)
M	=	Mach number	
$\bar{p}$	=	Roll Rate	(radians/s)
p	=	Non-dimensional roll rate	
P	=	Pressure	(Pa)
Θ	=	Angle of attack	(degree, °)

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