2ND EUROPEAN CONFERENCE FOR AEROSPACE SCIENCES (EUCASS)
BRUSSELS, BELGIUM ; JULY 1 – 6, 2007

Hypersonic Flow Interaction of Pitched Short Lateral Plates on Blunted Cone Configuration

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Abstract
Hypersonic flow interactions for short protuberances installed on a standard blunt cone configuration were studied, aerodynamic effects were found analogous to lateral jet-interactions for Mach 5, 6 and 9.7 on a conic geometry at incidence. Static aerodynamic coefficients and axial pressure distributions were determined using CFD tools for flow interaction effects of pitched short protuberance geometries of cylindrical cross-section. It has been concluded that pitched short protuberance installed on a blunted cone causes an increase in net force through altering pressure distribution, with consequent development of aerodynamic pitching moment, forward pitching of protuberance was found to be more effective in comparison with an aft inclination, while similarity in predicted pressure distribution using CFD analysis with an overall prediction accuracy of ± 10% was found with the experimental results in the hypersonic range.

Keyword: *Hypersonic flow, Blunt nose cone, Jet Interaction (JI), Short Protuberances, Pitched lateral plate, CFD, Axial pressure distribution, RCS.*

Nomenclature

M	Mach number
R_e/m	Reynold's number per unit length
α	Angle of attack [degree]
P	Local pressure [Pa]
P_{inf}	Reference pressure [Pa]
x	Axial distance on cone surface [m]
y	Normal distance on cylinder/ plate surface [m]
D	Protuberance cylinder/ plate base diameter, body diameter [m]
H	Protuberance height [m]
C_X	Axial drag force coefficient
C_m	Pitching moment coefficient
C_Y	Side force coefficient
X_{Cp}/L	Non dimensional centre of pressure
H/D	Non dimensional height of protuberance, plate/ cylinder
L	Length of the body [m]
q_∞	Non dimensional free stream dynamic pressure

1. Introduction

Side thruster is a highly responsive means for attitude control [1], generally, they are an effective means for maneuvering and controlling aerodynamic vehicles [2] to [4], configurations in flight either requires aerodynamic surfaces or jets to deliver required force in order to maintained desired stability; in absence of atmosphere, low velocity, lower dynamic pressure or in case of bodies of revolution type of geometries, supersonic jets are in vigorous use for attitude or roll control on vehicles undergoing atmospheric flight, upon encountering a crossflowing freestream reoriented to provide flow interactions, though jets in crossflow (JICF) is one of the classic problems of fluid mechanics, however, necessary data for aerodynamic applications are lacking [5]. For aerodynamic vehicles using aerodynamic control surfaces for any kind of maneuvering at high altitudes or at lower velocities encounter lower efficiencies of control surfaces, similar requirements for maneuvering of aerodynamic vehicles lead to an introduction of lateral jet positioned forward and aft for attitude controls [3]. Side thruster can produce large angle pull force relative to flight direction is a supplement to traditional aerodynamic control [1]. Jets in cross flow have applications in variety of technologically important systems and processes, in one form or another, JICF is involved in active flow control, aircraft performance and stability, etc. The presence of the high-momentum transverse jet in a cross flow has a similar effect as that of a solid body [6]. Reaction control systems, RCS and Divert and Attitude Control System, DACS concepts with the use of aerodynamic control surfaces to maneuver and close with the target by using flow separation on the interceptor body to achieve amplification factor greater than one [7]. As the jet-in-cross flow interaction is an inherently unsteady flow, accurate computational prediction of the mean flowfield behaviour generally requires knowledge of the instantaneous turbulent properties, which can come only from experiments [8] or to some extent from numerical simulations [1]; Jet/ plate interaction for hypersonic flows is difficult to produce numerically, owing to complexity of its nature, where strong bow shock interaction with weak boundary layer separation shock causes formation of a low density region upstream as well as downstream of the jet /plate [9], even many references containing substantial validation have not been in the open literature [10] to [13]. With this background of flow analogy for jet and plate/ short-protuberance, computational aerodynamic study using CFD analysis was conducted, presented in [14], [15], [16] and [23]; current work presented is with pitching of short protuberance forward and aft, to get a more realistic fluid flow situation, analogous to inclined jets, inferences presented here are for Mach 5, 6 and 9.7 flows for study of static aerodynamic coefficients and axial pressure distributions for a blunted cone geometry for a fixed H/D tilted forward and rearward from its mean position. With establishment of an analogous behaviour of a lateral plate / jet interaction with an incoming hypersonic flow at Mach 9.7 [14], investigation was made for Mach 5, 6 and 9.7 flows for blunted cone configuration at an angle of attack of negative 12 degrees, by modelling a jet of cold air as a solid short circular cylinder protuberance projected as a pitched lateral plate over a blunted cone mounted at the location of nozzle exit [17]. Single protuberance height equal to cylinder diameter was used and aerodynamic flow field behaviour for hypersonic free stream interaction with lateral short protuberance in pitched forward and aft positions were analyzed by calculating static coefficients and axial pressure distributions. Flow visualization was made through pressure contours and velocity vector plots. CFD calculations were made using PAK-3D [18], an in-house developed Navier-Stoke's solver and quantitatively good corroboration was found with the experimental pressure distribution trends reported in [19] and [20]. All the post processing was performed using post-processing software LOOK [22].

2. Geometry

The standard conic model is a blunted cone with half-cone angle of 10.4°, jet is represented as a short protuberance is at the same location where the nozzle exit is situated as in reference [17], i.e., at 417mm from the blunted nose. The diameter of the cylindrical plate is equal to the nozzle exit diameter which is about 14.2mm, and the height of the plate is taken as 1.0 D, pitched positions of the plate were defined as inclined forward and aft of its mean position. Geometrical features and details are as depicted in Fig. 1.

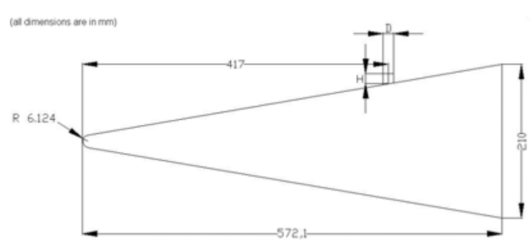

Figure 1: Blunted cone configuration with lateral short protuberance.

3. Grid Generation

Computational grid quality, regarding its density and packing required for Mach 5 to 9.7 flows was imposed from earlier studies conducted, refer [15] and [23] essential for capturing of flow details in the hypersonic range, satisfactory convergence with grid independence studies was employed. Entire grid generation was performed using the grid generation software PAK-GRID [21]. Structured grid is generated with a 180 degree gird for axisymmetric case. A typical grid used for Mach 9.7 computations for a blunted cone configuration with pitched short protuberance contained four blocks and 0.106 million grid points. Some grid details are elaborated and are as shown in Fig.2.

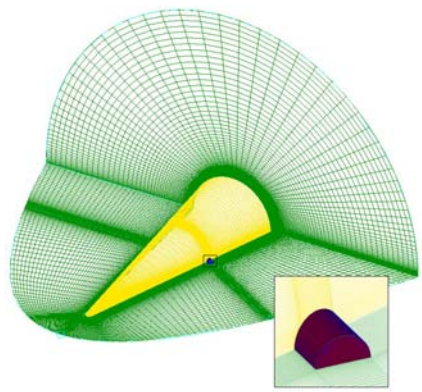

Figure 2 : Typical M= 9.7 (flow in positive x-direction) grid of pitched short protuberance (30^0 forward) installed on a blunted cone.

4. Boundary / Initial Conditions

Appropriate hypersonic inflow conditions for a half-body, 180 degree grid were used, while the extrapolation condition was applied at the outlet section, symmetric condition was employed at the symmetry plane and no slip adiabatic condition was imposed at the surface of the body as well as on the inclined short protuberance. The computation is performed with the Mach number, M = 5 to 9.7 with an angle of attack of zero and -12 degrees, air specific heat ratio, γ considered as 1.4 with a Reynolds's number, Re/m ranged from 4.8×10^6 to 2.47×10^6 .

5. Results and Discussion

Aerodynamic flow interaction behaviour of a pitched short protuberance installed on blunted cone geometry with the incoming hypersonic flow, axial pressure distribution was initially calculated on the leeward side of the body for an angle of incidence of negative 12˚ as protuberance is positioned on the leeward side of the blunted cone configuration. The axial pressure distribution in vicinity of a vertical protuberance is as shown in Fig. 3. The trend of pressure distribution for vertical protuberance showed similarity for Mach 5, 6 and 9.7 flows.

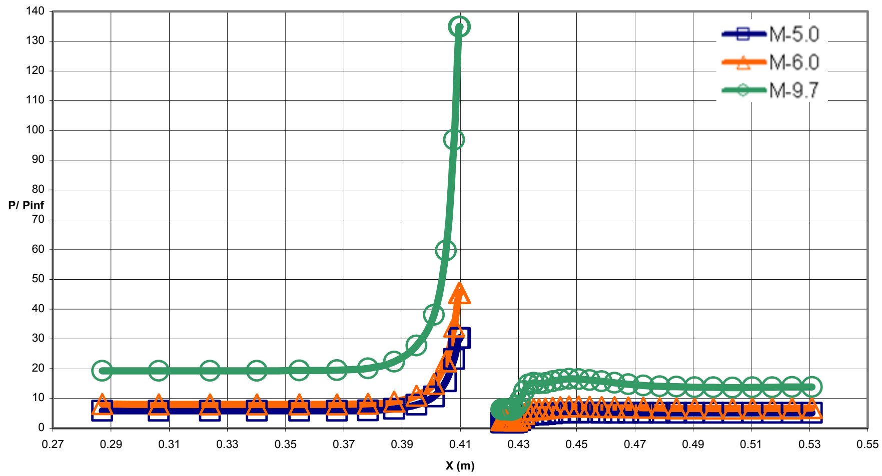

Figure 3: Leeward surface axial pressure distribution for vertical plate on a blunted cone at M = 9.7, α = -12 degrees.

After benchmark study of a lateral short protuberance, the same cylindrical geometry was studied by pitching it forward and aft of its mean vertical position, all inclination angles are considered from vertical plane to the centre line of the blunted cone, inclination considered as 45 degrees forward and aft for hypersonic flow at Mach 5 at -12 degree cone incidence, transversal pressure distributions were calculated along the plate height, and are as shown in Fig. 4.

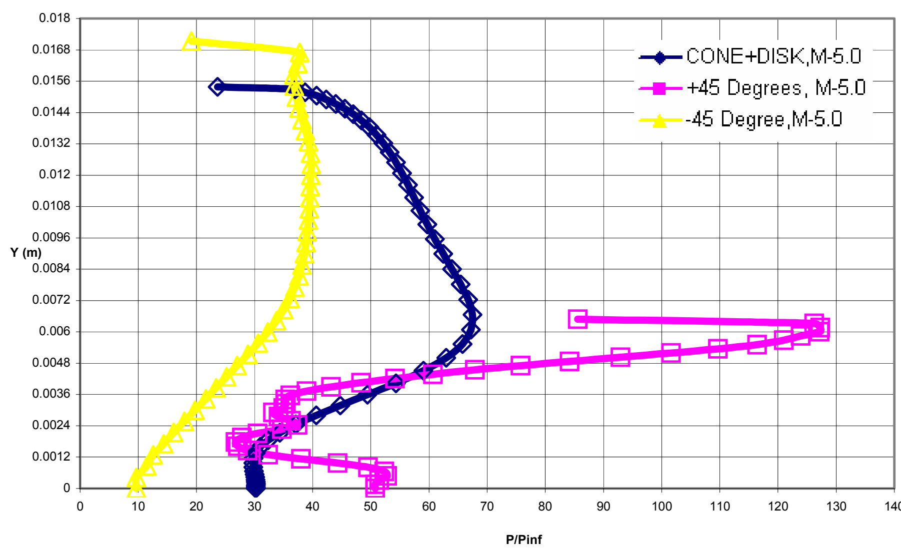

Figure 4 : Transversal surface pressure distribution on pitched plate on a blunted cone at M = 5, α = -12 degrees.

The rise in peak pressure value for a specific Mach is a representation of strong flow interaction, moreover a forward inclination of 45 degrees showed relatively stronger interaction in comparison with 45 degree aft pitching angle. Further to this analysis, study was made to vary pitch angle of short protuberance for Mach 9.7. For a pitched protuberance forward and aft for an inclination angle of ± 30 and ± 45 degrees, lateral pressure distributions on the cone surface in the meridian plane are computed and are as shown in Fig. 5. Comparison was made for peak pressure rise in both the forward inclinations (30 and 45 degrees) with the aft inclinations with Mach 9.7, showed relatively large flow interaction for the former situation. More rise in pressure is observed with a forward pitching of 45 degrees in comparison with 30 degrees forward deflection and all aft inclination angles is representative of a stronger shock-boundary layer interaction.

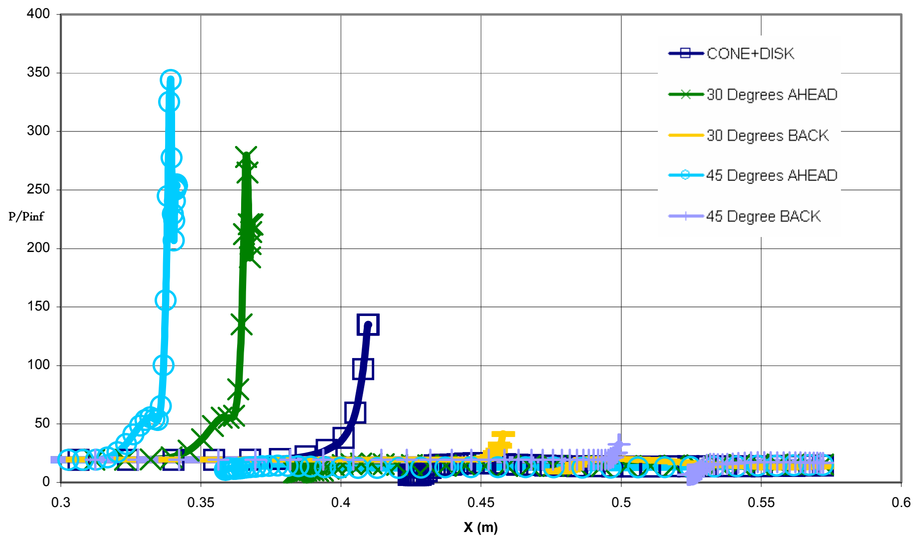

Figure 5 : Leeward surface axial pressure distribution for pitched short protuberance for Mach 9.7, α = -12 degrees.

On the quantitative analysis part, static aerodynamic coefficients were computed to quantify the effects of pitching forward and aft of the short protuberance at Mach 9.7 while blunted cone is at an angle of attack of zero and -12 degrees. Aerodynamic pitching moment created due to hypersonic flow interaction grossly showed a similar behaviour for forward pitched short protuberances in case of 30 and 45 degree forward tilt, so its usefulness is almost of the same magnitude and about 11 % more effective in comparison with the case of pitching it in an aft direction. Details of computed static aerodynamic coefficients for Mach 9.7 are given in Table 1 and Table 2 for 30 and 45 degrees tilt in a forward and aft direction, respectively.

Table 1: Static aerodynamic coefficients for 30 and 45 degrees forward pitched at M = 9.7.

Aerodynamic Coefficients	Forward 30 degrees pitch		Forward 45 degrees pitch	
	AOA = 0^0	**AOA = -12^0**	**AOA = 0^0**	**AOA = -12^0**
C_Y	-0.0191	-0.38615	-0.01529	-0.3813
C_X	-0.10139	-0.13958	-0.10112	-0.13979
C_m	0.009742	0.231935	0.006244	0.227524
X_{cp}/L	-0.51006	-0.60063	-0.40835	-0.59671

Table 2: Static aerodynamic coefficients for 30 and 45 degrees pitched aft at M = 9.7.

Aerodynamic Coefficients	Aft 30 degrees pitch		Aft 45 degrees pitch	
	AOA = 0^0	**AOA = -12^0**	**AOA = 0^0**	**AOA = -12^0**
C_Y	-0.01394	-0.40673	-0.00605	-0.40951
C_X	-0.09721	-0.13841	-0.09095	-0.13157
C_m	0.010336	0.253825	0.004702	0.256539
X_{cp}/L	-0.74159	-0.62406	-0.77695	-0.62646

Qualitative trends in the form of pressure contours, Mach plots and close-up of velocity vectors at various Mach numbers in vicinity of the pitched short protuberance in forward and aft directions are shown in Fig. 6 and Fig. 7, respectively.

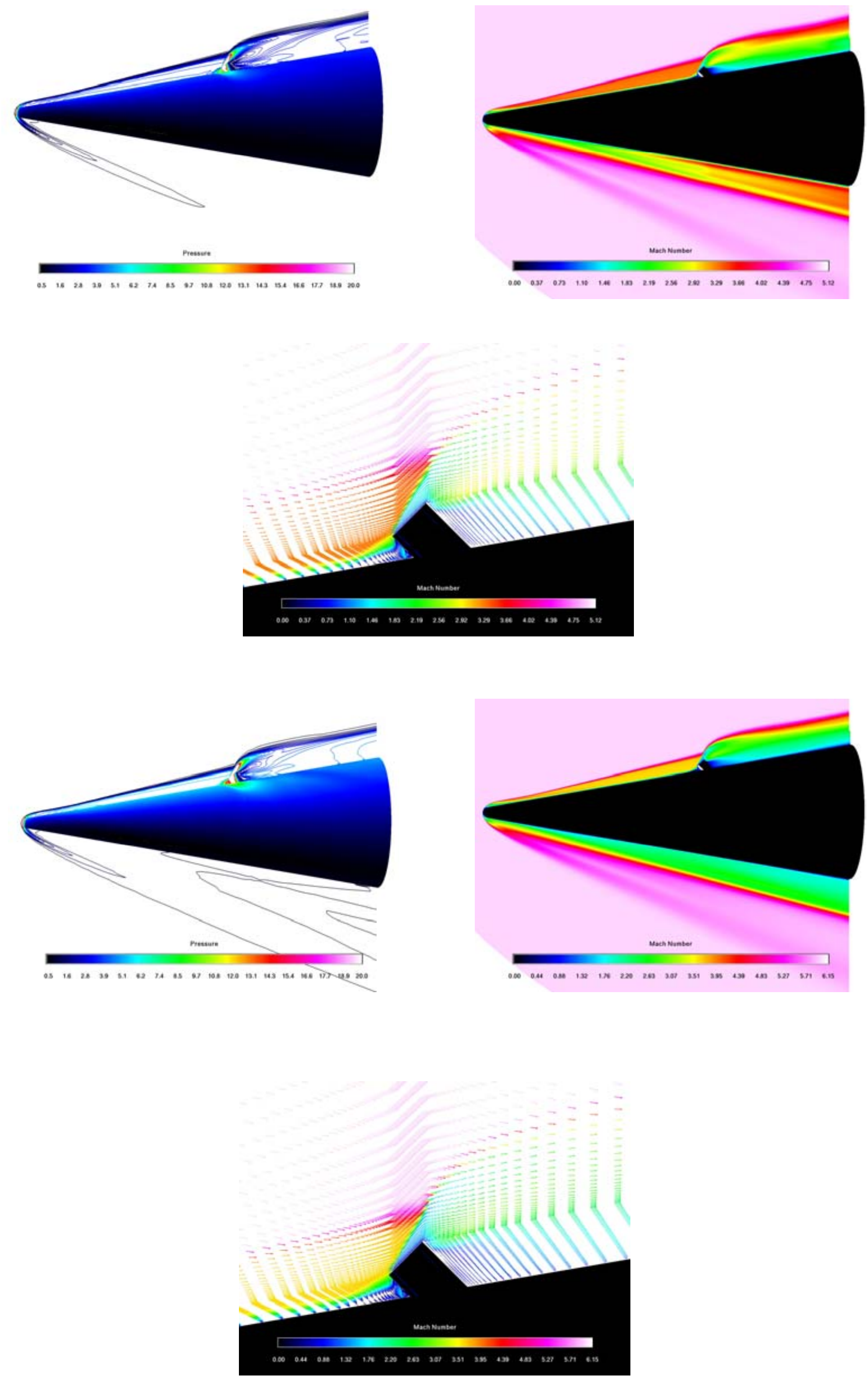

Figure 6 : Pressure contours, Mach plot and velocity vectors for lateral protuberance at 45 degrees pitched forward on blunted cone at Mach 5 and 6, respectively at an angle of attack of -12 degrees.

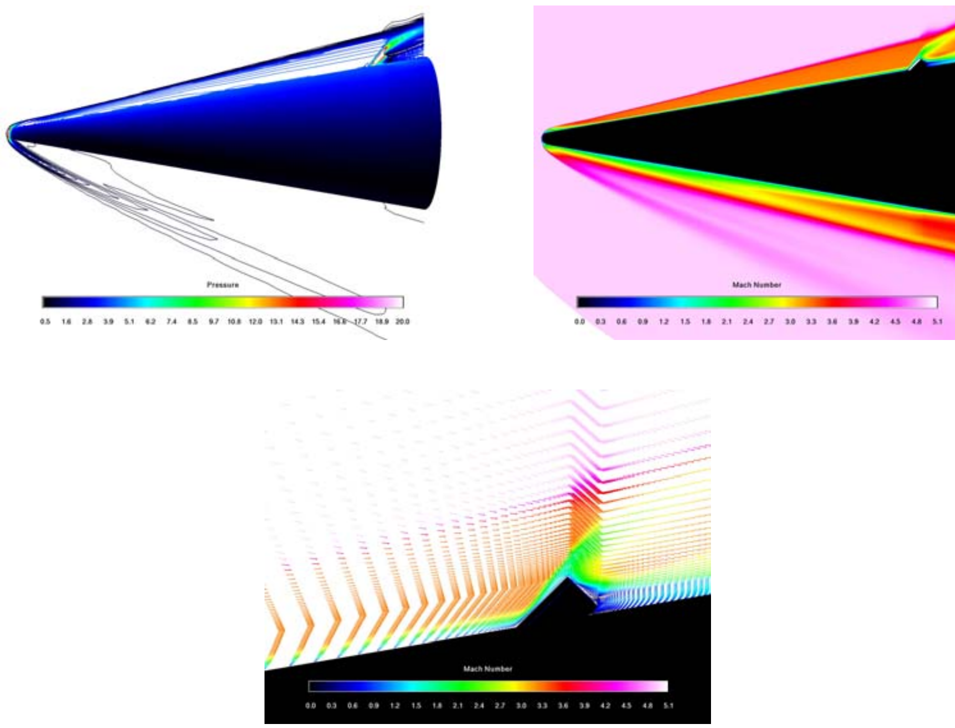

Figure 7: Pressure contours, Mach plot and velocity vectors for lateral protuberance at 45 degrees pitched aft on blunted cone at Mach 6.0 and angle of attack of -12 degrees.

6. Conclusions

1. The flow interactions for pitched short protuberances with cylindrical cross sectional geometry fixed to a blunted conic configuration were found qualitatively similar to lateral jet/ plate interactions in Hypersonic Mach 5 to 9.7 flow range. It has been concluded that forward pitched short protuberance installed on a blunted cone causes an increase in net force through altering pressure distribution, with subsequent development of aerodynamic pitching moment, stronger flow interaction was observed for 45 degree forward pitching of short protuberance.

2. The aerodynamic interaction of hypersonic flows for pitched short protuberance with H/D = 1 on blunted cone in hypersonic flow were found effective; usefulness of short protuberance for development of aerodynamic pitching moment in case of -12 degree angle of attack when installed at the leeward side of the blunted cone at Mach 5 and 6 was observed for forward pitching in comparison with aft inclination.

Acknowledgements

The author's are grateful to ASAC, Pakistan for providing computational and data processing support.

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