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CFD analysis of missile with altered grid fins to enhance aerodynamic efficiency in subsonic flow regime

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ABSTRACT: Grid fins are meshed control surfaces used on guided missiles and rockets. Grid structure has been proved aerodynamically more efficient in transonic and supersonic flow regimes comparatively with conventional planar fins but inadequate in subsonic flow. The objective of this work is to enhance aerodynamic efficiency of grid fins in subsonic conditions by altering its frame and web thicknesses based on Air-to-Air missile (AA-Adder) in comparison with planar fins and body alone missiles at different angle of attack ranging from $0^0 \leq \alpha \leq 12^0$ to evaluate the aerodynamic efficiencies. This was achieved by performing numerical analysis in low subsonic conditions specifically at Mach 0.3 signifying the sonic region in a computational fluid domain. Using Ansys workbench and Fluent applications for simulation the aerodynamic coefficients viz., lift, drag, and moments on missile envelope were calculated and validated with available Fluent and wind tunnel measurement data. The results demonstrated substantial improvement in the aerodynamic efficiency on altered grid fins and good agreement with the available data, therefore proving the efficiency of grid fins than planar fins on a missile in subsonic flow regime.

Keywords: *Air-to-Air missile, Grid fins, Planar fins, Sonic region.*

I. INTRODUCTION

In modern military terminology a missile is an unmanned guided weapon system intended to be fired to strike and destroy any targets using a warhead as its payload. Unlike conventional bombs with limited range and control, missiles are capable reaching farther distances at higher Mach numbers with precise guidance using advanced propulsion and control systems. The targeting and guidance system, flight system, propulsion and warhead are the four major systems in a missile and are further classified into various types based on specific mission requirements such as launch platform, target, range, guidance, and propulsion systems. All missiles are designed to propel during powered flight condition due to chemical kinetics occurrence inside engine using solid, liquid, hybrid, or cryogenic propellants and mostly controlled using external aerodynamic surfaces known as control fins for effectively maneuvering the missile towards its target.

Grid fins

Unlike conventional planar fins that look like miniature wings and are widely used as missile control surfaces, grid fins are unconventional means of missile control surfaces structured by smaller intersecting planar surfaces to craft individual cubes or triangle shaped cells covered with an outer frame that is inherently stronger allowing the lattice walls to be thin structured and mounted perpendicular to the direction of airflow allowing air to pass through the grid cells.

Grid fins were used on various Soviet missile designs since the 1970s, particularly on ballistic missiles like the SS-12, SS-20 Saber, SS-21 Scarab, SS-23 Spider, and SS-25 Sickle. These fins have also been used on Russian spacecraft including the N1 lunar rocket and the Soyuz TM-22 capsule as emergency drag brakes. The latest SpaceX rocket uses Grid fins for re-entry, Perhaps the most recognized appearance of grid fins to date is on the Russian AA-12 'Adder' medium-range air-to-air missile employed in this study. Aerodynamics of grid fins has been investigated since 1985 by the U.S Army Aviation and Missile Research and Development Centre (AMRDEC), Huntsville, Alabama (Washington and Miller 1998, Miller and Washington 1994, and Washington and Miller 1993) Further [1] and [2] performed inviscid calculations to study the aerodynamic efficiency of grid fins. These investigations indicated that grid fins have certain advantages over conventional planar fins such as the ability to maintain lift at higher angle of attack, as grid fins do not have the same stall characteristics of planar fins and requiring very small hinge moment can reduce the size of control actuator systems. The retractable mechanism of folding down the grid fins onto the missile body serves as a storage design advantage. While, the main disadvantage higher drag than that of planar fins, although certain techniques for minimizing drag by altering the grid fin frame cross-section shape were demonstrated (Miller and Washington 1994). These studies also showed that grid fins experience a loss in control effectiveness in the transonic regime due to flow choking in the individual cells.

The present study is an extension of the work based on grid fins in comparison with planar fins on a missile cases by [1] which proved the efficiency of grid fins in super-sonic flow regime at Mach 2.5. Further [2] found out that grid fins performed poorer than planar fins on a canard controlled missile, and further studies from [3] and [4] proved the excellent supersonic control characteristics of grid fins and certain methods to reduce drag by altering the frame and web thicknesses were proposed. Conclusions from [8] proved that grid fins are effective in improving the stability of a missile in subsonic and transonic flow, the present study intends to prove sub-sonic efficiency of grid fins at Mach 0.3 and various angles of attack (α) ranging from 0 to 12 degrees by simulating the flow field over the missile using Ansys workbench. The geometry was adapted from AA-Adder Missile configuration and design of the 3-dimensional model was carried out in Computer Aided Three Dimensional Interactive Application (CATIA V5) software, further the design is imported to Ansys workbench 14.5 for generating a mesh and specifying the boundary conditions, Fluent application was used to simulate the flow field at Mach = 0.3 and evaluate the aerodynamic force coefficients and Flow field structure at different angles of attack over the missile without fins with Planar fins and with Grid fins.

II. NUMERICAL APPROACH

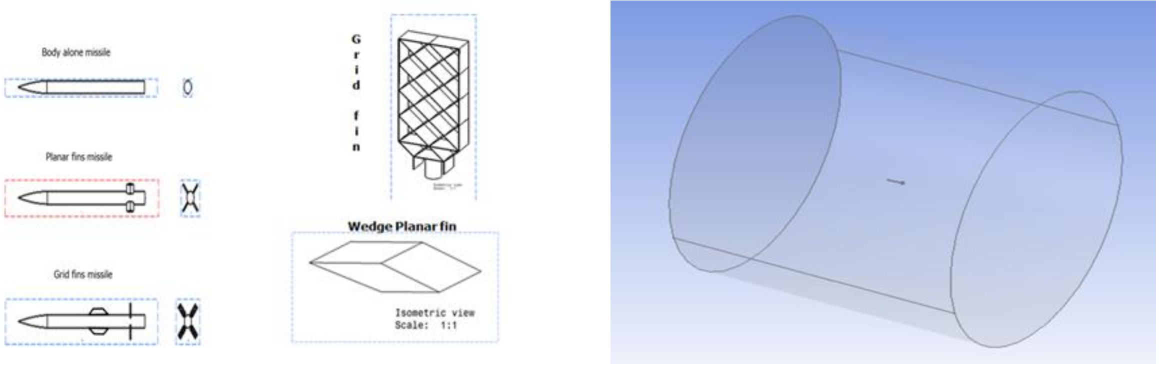
Geometry of the missile

The geometry of Russian made missile AA- Adder which is also a base model for the current indigenously Indian made missile ASTRA has been chosen for this study based on the available features / models with a similar body and different control sections such as the variants of grid fins and planar fins configuration used on different classes of the missile which is useful for this study mainly emphasising on improving the performance of grid fins over a missile in comparison with planar fins.

The model of the missile body is 3600 mm in length with a diameter of 200 mm and 830 mm tangent ogive with the fins located 414 mm ahead of the aft end of the missile. Three such designs were modelled as shown in Fig.1 to analyse and evaluate the performance of grid fins missile in comparison with planar fins missile and body alone missile without control sections.

Fig. 1 Geometry of the missile, control fins and fluid domain

Fig. 1 [a] Sketch of missile and control fins **Fig. 1 [b]** Computational fluid domain



The dimensions of planar fins configuration adapted from one of the Adder variants which has a 250 mm long wedge shaped airfoil cross section with a 200 mm chord and 10 degrees wedge angle. Grid fins had to be altered to match the goal of this study, for which the currently existing configuration of grid fins on Adder which is 250 mm in length, 100 mm wide with a 35 mm chord has been altered by increasing the frame thickness from 1 mm to 2 mm and web thickness from 0.75 mm to 1.5 mm which was found to be appropriate in providing enough lift required to improve the missile performance compared to planar fins in sub sonic flow regime.

The missile as fixed in a three dimensional cylindrical domain represents a Right -handed system with the x,y,z axes coinciding with the missile's roll axis, pitch axis and yaw axis respectively. The domain is 1:8 times the length of the missile from its centre of gravity in all directions to effectively capture the flow features without disturbances from the domain wall and accurately capture flow over the missile. The fluid domain in all the cases is 57600 mm in length with a distance of 28800 mm between the missile and the wall of fluid domain.

III. MESHING

In the Pre-processing stage three models of the missile have been discretized to generate a mesh in the fluid domain in Ansys workbench 14.5 Meshing module and a three dimensional unstructured tetrahedral mesh with wedge elements comprising over 2.5 million cells has been generated using Patch conforming method for all the cases at different angle of attack using the minimum mesh size in the control volume of 5e-04 m (0.5 mm) and e-3 m (1 mm) for grid independence studies to meet the accuracy standards of the study and also to be apt for the geometry of the grid fin missile which has 1.5 mm web thickness that allows to generate at least three cells in the fin area to accurately capture the boundary effects of the flow. Using this accuracy of minimum mesh size also allows generating minimum four cells in the grid fin frame area with a thickness of 2mm. Therefore the minimum mesh size of 0.5 mm or 5e-4 m has been fixed to capture the flow over grid fins effectively and also to meet the international standards of mesh accuracy. Using the minimum mesh size 5e-04 m and the maximum mesh size for each case has been reduced accordingly from actual default settings to a relevant mesh size that increases the accuracy of the problem and not exceeding the CPU capability limits. The mesh over the missile in each case was further modified by adding Inflation layers over the missiles in each case at to capture the boundary layer flow accurately. Certain factors like the advanced size function, fine relevance centre, high smoothing, and adaptive mesh growth rate and transition ratio have been adjusted to values as shown in the table to reach the accuracy standards that were cross checked with the aspect ratio and maximum skewness value that has not exceeded 0.90 with tetrahedral mesh. The meshed files as represented in Fig.3&4 have been exported to Fluent for further analysis.

Fig.2 Mesh of the missile in fluid domain

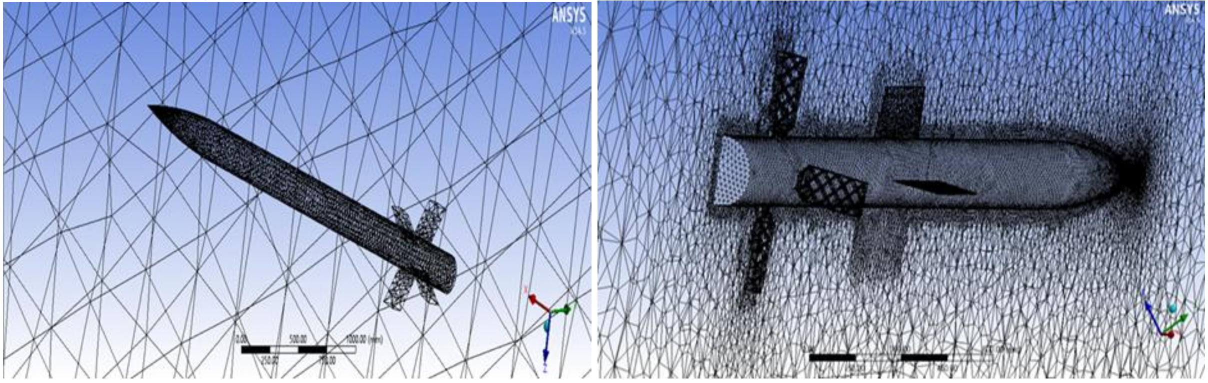


Fig.2 [a] Mesh of Planar fins mis

Fig.2 [b] Mesh of Grid fins missile

IV. SOLUTION

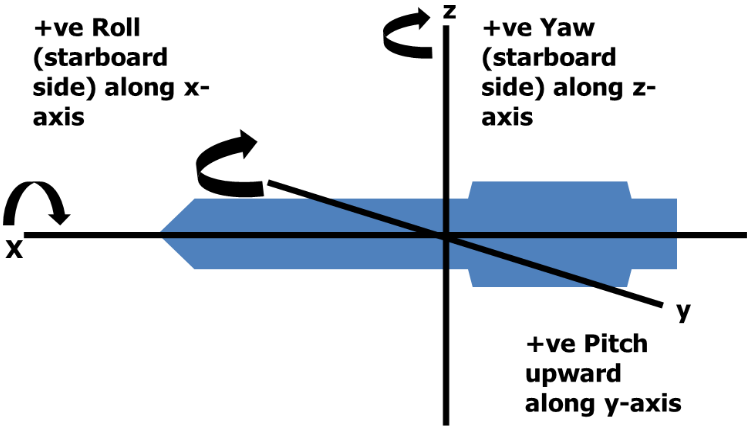
4.1 Solution methodology

The simulations were performed for three different cases of body alone, planar fins, grid fins missiles by simulating Sub-sonic flow (Mach 0.3) at different angle of attack (∝ = 0, 4, 8 & 12) for 12 cases at similar flow and boundary conditions to investigate the aerodynamic flow field structure around the missile using different control surfaces. The viscous and pressure forces along the missile body, planar fins and grid fins surfaces of three models at different angle of attack in 12 cases were simulated using the Fluent Post-processor in Ansys workbench to calculate the aerodynamic coefficients and determine the aerodynamic efficiencies of planar fins and grid fins and prove the improved aerodynamic efficiency of altered grid fins in sub-sonic flow regime. Having modelled the actual precise dimensions of the missile which is 3.6 meters in length required a longer fluid domain which is eight (8) times the length of the missile measuring 57.6 meters long to accurately capture the boundary layer effects over the missile and its control surfaces which increased the simulation time for each iteration and the number of iterations to achieve converged solutions for all the 12 cases.

The simulations were carried out using Density Based Coupled solver with Implicit formulation and “Least square cell based” Gradient discretization method has been applied with Second order upwind scheme for better accuracy. Mentor $k - w$ SST (Shear stress transport) two-equation eddy- viscosity turbulence model was adapted to capture adverse pressure gradients and flow separation over missile configuration and its control surfaces.

The missile in the fluid domain is represented as a right handed system with the x axis coinciding with the longitudinal axis of the missile (rolling moment), the y axis is oriented on the missile’s lateral axis (pitching moment) and the z axis oriented upward in the missile’s normal axis (yawing moment) which suggests that the forces acting on the missile are positive while coinciding with the positive coordinate axes (as shown in fig.3). The rolling moment is positive as the missile rolls clockwise in a forward view from the aft end of the missile. Similarly, the pitching moment is positive with an upward movement of the nose and the yawing moment is considered positive if the nose moves towards the starboard side (right side) of the missile.

Fig.3 Missile with Boundary conditions in the domain



4.2 Solution parameters

Based on the assumed operating altitude at 30,000 feet as launched from a combat aircraft the operating pressure and temperature conditions have been calculated with respect to the speed of the missile (Mach no = 0.3) in sub-sonic flow regime, further the static pressure (35385 Pascal) and static temperature (235 kelvin) conditions are applied while using the pressure far-field boundary conditions which is applicable only when the density is calculated using Ideal-gas law as in this case.
From the formula for static pressure,

$$\frac{p_0}{p} = \left[1 + \left(\frac{\gamma-1}{2}\right)M^2\right]^{\frac{\gamma}{\gamma-1}} \qquad \text{(Formula.1)}$$

Where,
p_0 = total pressure
p = static pressure
γ = Density (1.4 for air)
M = Mach no: 0.3

For static temperature,

$$\frac{T_0}{T} = 1 + \left(\frac{\gamma-1}{2}\right)M^2 \qquad \text{(Formula.2)}$$

Where,
T_0 = total temperature
T = static temperature
γ = Density (1.4 for air)
M = Mach no: 0.3

In reality the far-field air would be stationary, while wind tunnels attempt to replicate this phenomenon by using filters or grids to obtain low turbulence intensity at the inlet it is also possible to achieve that computationally by selecting “Intensity and Length scale” Turbulence specification method and setting the intensity to 0.01 % (0.01 –0.05% for wind tunnel problems) and Length scale based on the estimated maximum boundary layer thickness of 50 mm for which the length scale was calculated to be 0.4 × 0.05 = 0.02m. Density was chosen as Ideal-gas based on pressure far-field boundary conditions and Viscosity using Sutherland law based on the kinetic theory of ideal gases which most often gives fairly accurate results. The simulations carried took about 2 to 3 minutes per iteration by using a single processor which took around 1000 iterations for each case to get converged solutions with second order accuracy taking approximately 8 to 10 hours of CPU time for each case of the 12 cases finding the aerodynamic efficiency of grid fins over planar fins on a missile in subsonic flow regime.

V. RESULTS

The Fluent results of aerodynamic coefficients, forces and moments were analysed for comparative studies for the twelve cases of the body alone, planar fins and grid fins configurations of the missiles at different angle of attack from 0^0 to 12^0 to examine the aerodynamic forces and moments acting over the missile airframe, the aerodynamic data was generated from Fluent Post-processor and further the results data were exported to CFD-Post and Tecplot360 which enabled further investigation of the aerodynamic flow field behaviour over the missile of three different cases at different angle of attack .

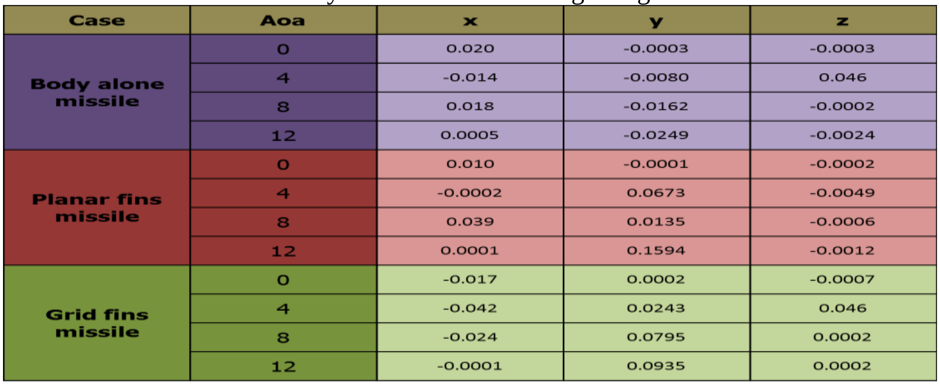
5.1 Aerodynamic forces and moments

The aerodynamic forces and moments represented as the coefficient of lift, coefficient of drag, and pitching moment coefficient data have been extracted from the Fluent results from the twelve case studies and plotted by comparing the data with previous research work from [1] which proved grid fins as efficient control surfaces on missiles than planar fins in super-sonic flow regime at Mach 2.5. Therefore the results were validated with this data to compare the efficiency of grid fins on altering the fins frame and web thicknesses in sub-sonic flow regime at Mach 0.3 and also with DERA (Simpson 1997) wind tunnel measurement data and a good agreement with the validated data was observed as plotted in the following sections the following tables and plots represent the forces and moments data of the missile in three different cases at different angle of attack ranging from 0 to 12 degrees as along X, Y, and Z axes of the missile considered as the Roll, Pitch and Yaw axes respectively which enables further investigation of aerodynamic force coefficients data and validation of the same. Table.1 and Table.2 represent the values of aerodynamic forces and moments in the three-axis coordinate system in x, y, z axes for the body alone missile, planar fins missile and grid fins missile at different angle of attack ranging from 0^0 to 12^0 at flow conditions simulating subsonic flow at Mach 0.3 which is considered as the sonic region where the flow transition occurs from laminar to turbulent flow.

Table.1 Aerodynamic Forces acting along the missile

Case	Aoa	x	y	z
Body alone missile	0	-0.0245	0.0001	-0.0003
	4	-0.0273	0.0002	0.0117
	8	-0.0331	0.0015	0.0277
	12	-0.0409	0.0070	0.0469
Planar fins missile	0	-0.0397	0.0002	-0.0001
	4	-0.0872	0.0036	0.0648
	8	-0.0210	0.0007	0.0295
	12	-0.1084	0.0013	0.1749
Grid fins missile	0	-0.1288	0.0003	0.0002
	4	-0.1374	0.0003	0.0900
	8	-0.1246	0.0160	0.1629
	12	-0.1831	0.0003	0.2797

Table.2 Aerodynamic Moments acting along the missile



Case	Aoa	x	y	z
Body alone missile	0	0.020	-0.0003	-0.0003
	4	-0.014	-0.0080	0.046
	8	0.018	-0.0162	-0.0002
	12	0.0005	-0.0249	-0.0024
Planar fins missile	0	0.010	-0.0001	-0.0002
	4	-0.0002	0.0673	-0.0049
	8	0.039	0.0135	-0.0006
	12	0.0001	0.1594	-0.0012
Grid fins missile	0	-0.017	0.0002	-0.0007
	4	-0.042	0.0243	0.046
	8	-0.024	0.0795	0.0002
	12	-0.0001	0.0935	0.0002

5.2 Plots

The aerodynamic force coefficients and moments acting on the missile such as the coefficient of lift, coefficient of drag, and pitching moment coefficient acting over the missile along x, y and z axes and the pitching moment, rolling moment and yawing moment acting along the same are plotted from the aerodynamic data by comparing the forces and moments along the body alone, planar fins and grid fins missiles. Form the data of coefficient of lift C_l Vs α it is observed that grid fins performed similar to planar fins at 0 angle of attack, Although by increasing the angle of attack at 4 degrees planar fins seem to generate a little more lift than grid fins but beyond that it is clearly observed that grid fins generated maximum lift than planar fins and body alone missile at a critical angle of attack 8^0 which is considered to be the best performance range for grid fins as the coefficient of lift decreases beyond 12^0 angle of attack.

Fig.4 Aerodynamic force coefficients Vs ∝ (alpha)

Fig.4 [a] C_l Vs α plot for body alone, planar fins and grid fins missiles

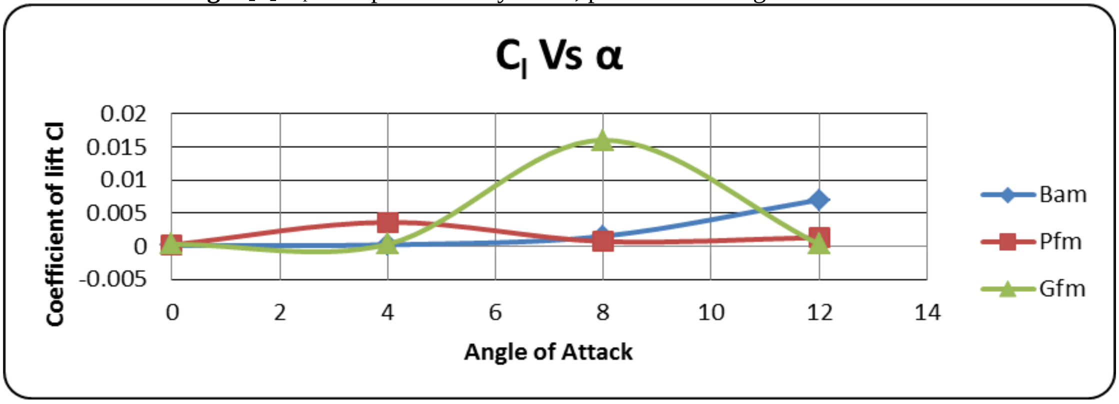


Fig.4 [b] C_d Vs α plot for body alone, planar fins and grid fins missiles

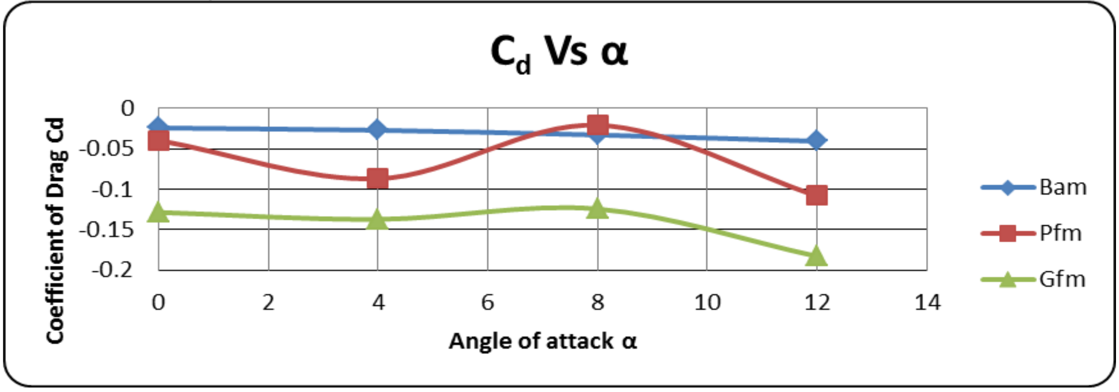
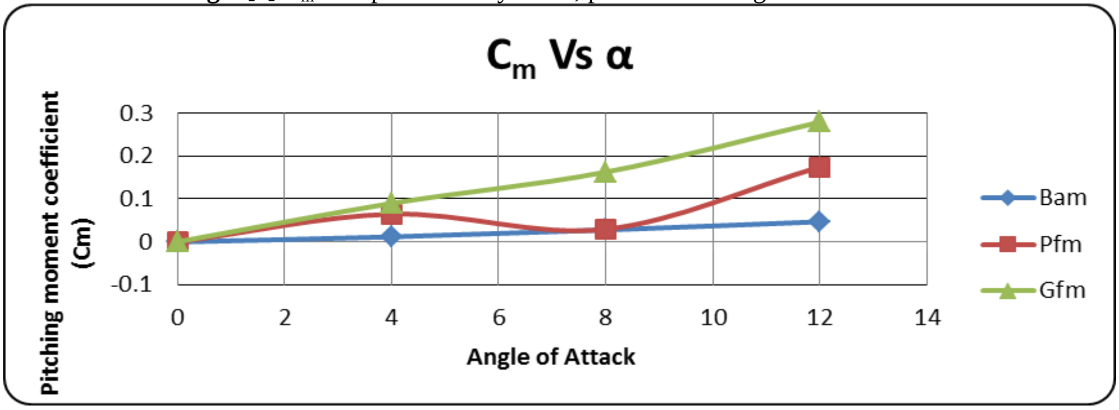


Fig.4 [c] C_mVs α plot for body alone, planar fins and grid fins missiles



The data from the plots in fig.4 representing the coefficients of lift drag and pitching moment that are compared between body alone, planar fins, and grid fins missiles proved hat altering grid fins web and frame thicknesses improved its aerodynamic efficiency and grid fins performed better than planar fins on a missile at Mach 0.3 in sub-sonic flow regime. The plot for C_d Vs α illustrates the reduced coefficient of drag (C_d) on grid fins which indicates the optimistic performance of altered grid fins as the drag is lesser the performance of grid fins is improves than that of planar fins. Similarly the Pitching moment coefficient that is considered to be practical at the aerodynamic center of the missile instead of its center of pressure and is a moment that has to be balanced to maintain requisite lift, from C_m Vs α at different angle of attack as it is gradually increased from 0^0 to 12^0 grid fins missile generated a higher aspect of pitching moment coefficient (C_m) than planar fins missile which again proved the improved performance of altered grid fins over a planar fins missile.

Fig.5 Aerodynamic Moments Vs ∝ (alpha)

Fig.5 [a] Rolling moment Vs α plot for body alone, planar fins and grid fins missiles

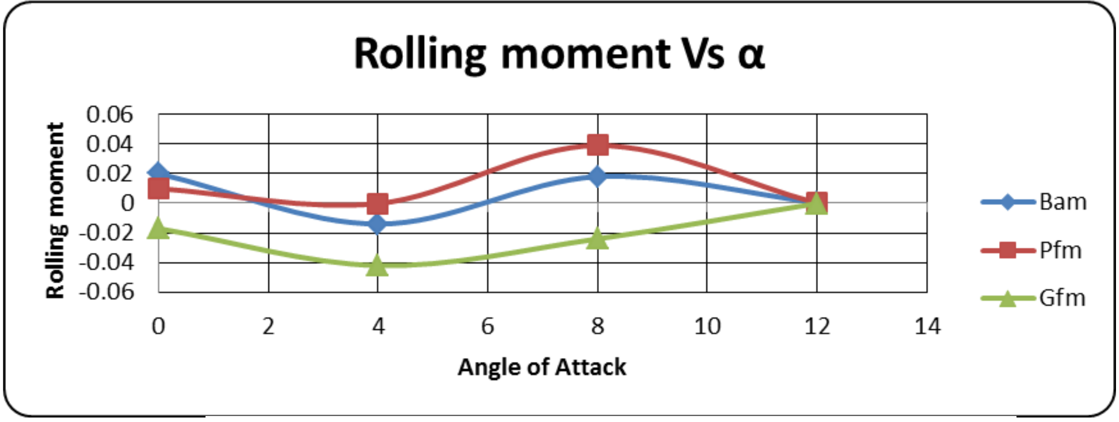


Fig.5 [b] Pitching moment Vs α plot for body alone, planar fins and grid fins missiles

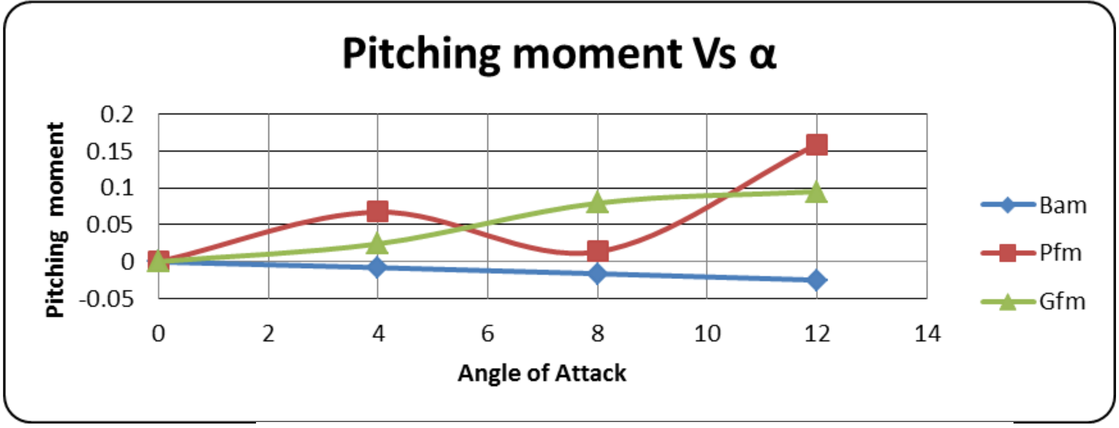
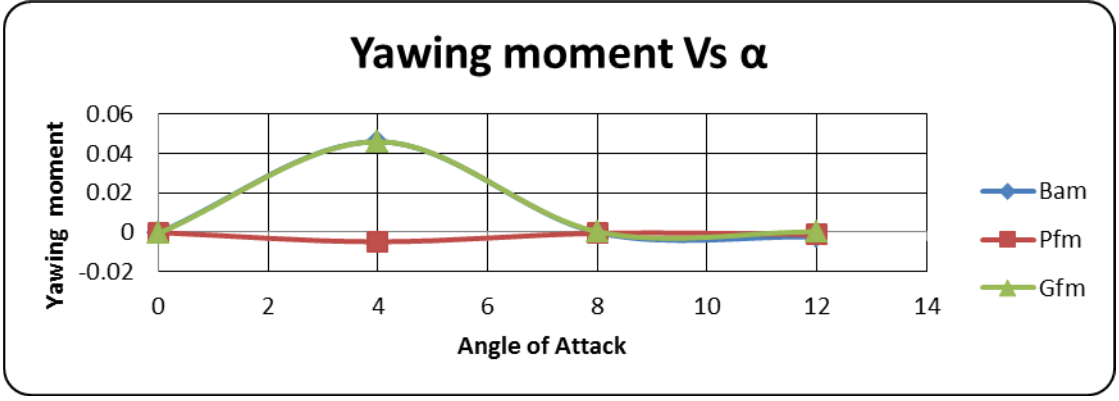


Fig.5 [c] Yawing moment Vs α plot for body alone, planar fins and grid fins missiles



From Rolling moment versus Alpha (∝) for the three cases it is observed that though grid fins missile experienced much lesser or negative rolling moment as the planar fins missile experienced a positive rolling moment that indicates instability as it is inconsistent unlike the grid fins missile that improved as the angle of attack is increased this suggests that grid fins missile is aerodynamically more stable and effective with increased stability and roll control effectiveness over body alone and planar fins missiles though this ability is noticed to reduce at higher angle of attack at 12^0 ∝ initially from 0^0 *to* 8^0 grid fins controlled the roll effectively according to the maximum effect of (C_l) at 8^0 angle of attack. The moment acting along the missile's lateral axis (y-axis) determines the total moment that has to be balanced using the lift generated and acting along the pitch axis of the missile. Therefore lesser pitching moment on the missile improves its performance by decreasing the forces required to counter the moment acting on the missile and the plotted data indicates that though the body alone missile case has generated much lesser pitching moment because of the absence of control surfaces, Grid fins missile experienced lesser and consistent pitching moment than planar fins proving its control effectiveness in subsonic flow regime. The Yawing moment which is the torque produced along the missile's z-axis (yaw axis) indicates that yawing moment on grid fins missile is higher at initial angle of attack at $4^0 \propto$ but it is substantially reduced as the angle of attack is increased and similar to the body alone and planar fins missiles at 12^0 angle of attack. Therefore the plotted data proved the enhanced performance of altered grid fins compared to planar fins as it has generated higher values of coefficient of lift (C_l) at a critical angle of attack ($\alpha = 8^0$) which will be followed throughout the comparative studies.

5.3 Validation with Fluent and experimental data at M_∞ 2.5

The obtained aerodynamic results were further validated with fluent and wind tunnel measurement data from [1] which proved the supersonic efficiency of grid fins, [2] conducted validation studies with [1] as an extension of the study in subsonic flow and concluded that grid fins are inefficient on canard controlled missiles. Based on this reference the current study focuses to improve the performance of grid fins on a missile by removing the canards in subsonic flow regime by altering its frame and web thicknesses and is evaluated for accuracy.

Fig.6 [a] Lift Vs α of grid fins missile

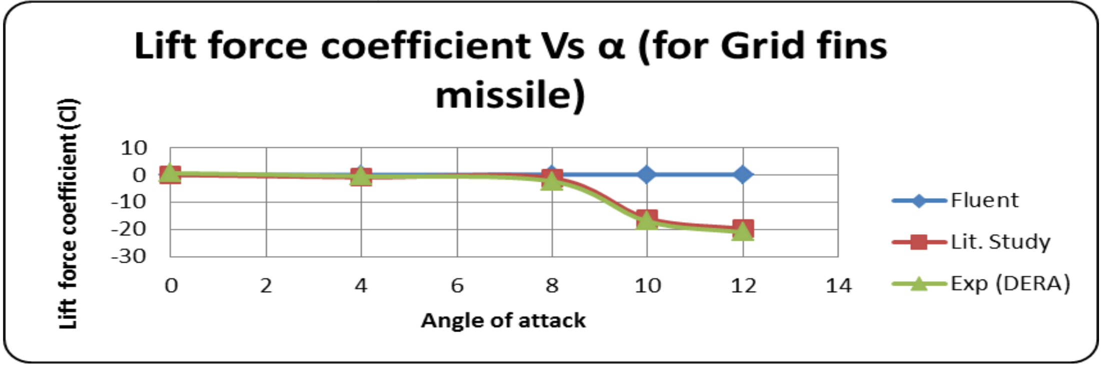


Fig.6 [b] Drag Vs α of grid fins missile

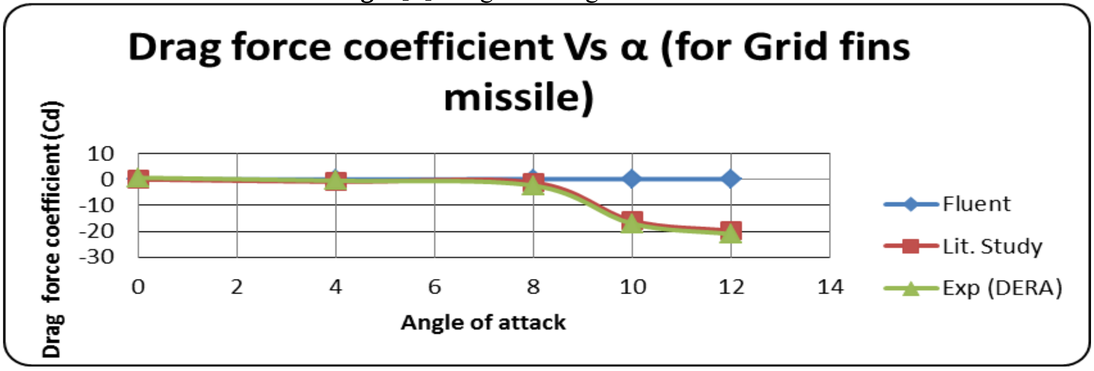
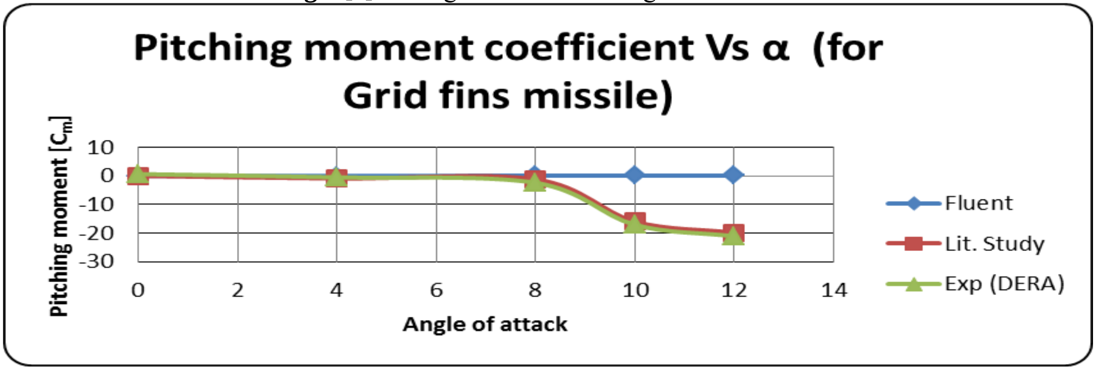


Fig.6 [c] Pithing moment Vs α of grid fins missile



The results were compared and validated with the aerodynamic data from [1] to be compared with the available data that proved grid fins as efficient control surfaces than planar fins on missiles. The plotted results proved that lift, drag forces and the pitching moment data generated from the current study are similarly much closer to the validated results with increase in angle of attack (α) from 0^0 to 8^0 and substantially reduced compared the validated results only beyond 8^0 as the angle of attack (α) is further increased up to 12^0 as shown in the following plots which is due to the supersonic flow characteristics in [1].

5.4 Numerical calculations

From the extracted aerodynamic Fluent data, the Lift, Drag, and Lift/ Drag ratio have been calculated for the three cases, Viz. Body alone missile, planar fins missile, and grid fins missile at different angle of attack (α) from 0^0 to 12^0 using the formulae as shown below for all the twelve (12) cases from the current study.

For Lift,

$$L = \frac{C_l . \rho . V^2 S}{2} \qquad \text{(Formula 3)}$$

For Drag,

$$D = \frac{C_d . \rho . V^2 S}{2} \qquad \text{(Formula 4)}$$

Where,

C_l= Coefficient of lift
C_d= Coefficient of drag
ρ = Density
V = velocity
S = Missile surface area

Based on the values of lift and drag (in pounds) the Lift/ Drag ratio has been calculated and plotted along with the data of major aerodynamic force coefficients, the coefficient of lift (C_l) and coefficient of drag (C_d) to find out the maximum lift/ drag ratio that can be generated at the best range of angle of attack compared with the aerodynamic force coefficients which was found out to be at α = 8^0 for the grid fins missile as the best range of performance from the data plotted.

From the data it is evident that altered grid fins are more efficient than planar fins on a missile in subsonic flow and the data suggests that the best range of performance has been identified at an angle of attack α = 8^0 for grid fins missile to perform effectively with minimum uncertainties in its flow field observed at Mach 0.3 in subsonic conditions.

Fig.7 Lift force report (in pounds)

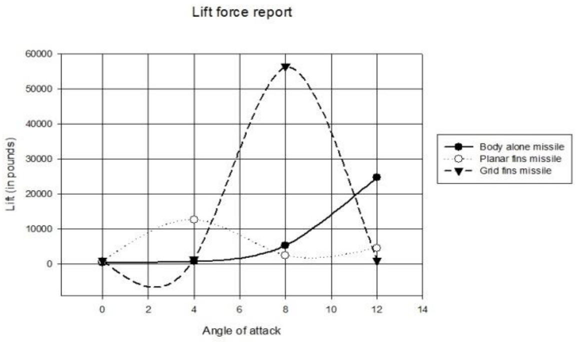


Fig.8 Drag force report (in pounds)

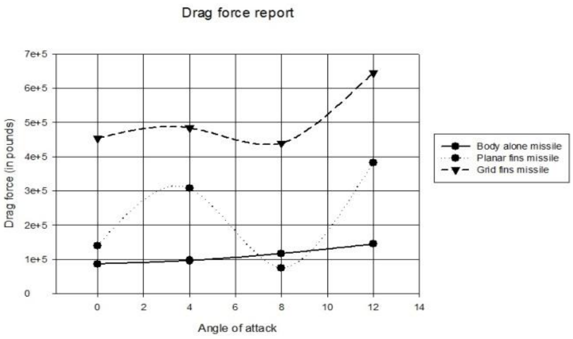


Fig.9 Lift/ Drag Ratio Vs α

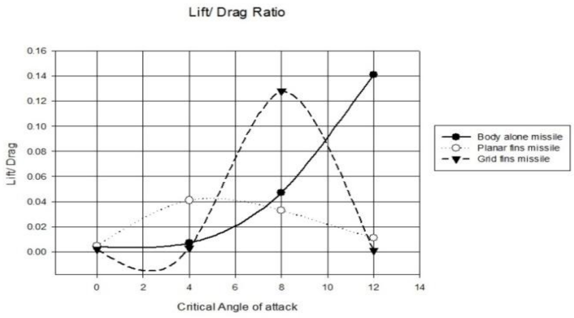
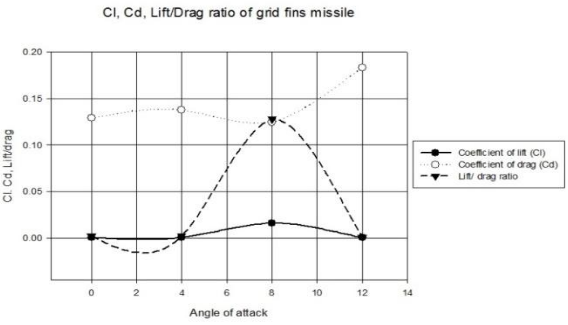


Fig.10 C_l, C_d, Lift/ Drag ratio for grid fins missile



VI. CONCLUSION

Based on the aerodynamic coefficients and moments plotted along the missile in the body alone, planar fins and grid fins cases and the validated data it is proved that altered grid fins have performed effectively than planar fins in the sonic region by simulating subsonic conditions at Mach 0.3 and the results showed a good agreement with the validated Fluent and wind tunnel measurement data in the best range of performance up to $\alpha = 8^0$. Therefore, it is proved that alteration of grid fins by increasing its frame and web thicknesses twice the actual size on an Air-to-Air Missile (AA-Adder) can significantly increase the lift generated and also enhance the overall aerodynamic performance of grid fins on a missile in subsonic flow regime. The results proved the stability achieved by grid fins on a missile compared to planar fins as higher and effective on an Air-to-Air missile by altering grid fins and thus incite the use of grid fins on missiles launched from a combat Aircraft by demonstrating its effectiveness in subsonic flow regime which is crucial for a missile to remain stable and operate effectively at the launch phase even before reaching the sound barrier in case of a supersonic cruise missile. Therefore, the results suggest future work on this design of altered grid fins as compared and proved efficient than planar fins in subsonic flow regime to further flow conditions at transonic and supersonic speeds on a missile across its flight path to ensure effective performance of grid fins throughout the mission operating phase from launch, glide to striking its target and prove the efficiency of grid fins than planar fins as missile control surfaces by effectively manoeuvring throughout the flight path on Air-to-Air missiles.

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