ANALYSIS OF GRID FINS AS EFFICIENT CONTROL SURFACE IN COMPARISON TO CONVENTIONAL PLANAR FINS

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Abstract

This paper presents a numerical study of aerodynamic characteristics of grid fins and conventional fins which have been used on various air launched munitions to control their trajectory. Computations were performed at Mach 0.5, 0.9, 1.5, 2.0 and 2.5 at five angles of attack between 0 and 20 degrees for the grid fin and conventional planar fin. Validation of the results was done by comparing the computed aerodynamic coefficients for the conventional fin with analytical results and for the grid fin with wind tunnel data. Good agreement in results was observed for both the fins. For the grid fin, the aerodynamic coefficients were within 1%-7% of the wind tunnel data. For the conventional fin, the coefficients were within 1%-5% of the analytical data. The simulations were successful in predicting the flow behavior over the stand alone grid fin in subsonic and supersonic regimes and showed their improved control effectiveness and aerodynamic characteristics over the conventional fin.

1 Introduction

Grid fin is an unconventional lifting and control surface with a paneled framework of flow channels like a honeycomb structure [1]. The outer frame supports an inner grid of intersecting small chord planar surfaces through which the air passes. Interest in grid fins as efficient tail control surfaces and their preference over conventional fins can be owed mainly to their better performance at high Mach numbers and high angles of attack. The smaller chord results in little variations in the position of center of pressure [2] and very low hinge moments over a wide range of mach numbers, reducing the size of the control actuator systems. Other advantages include high strength-to-weight ratio [2] and better stall characteristics. With their ability to fold along the munitions body which makes storage and transportation easier, they have become attractive for weapons designed for internal weapon bays on stealth aircraft [3]. The main disadvantage is the higher drag and choking of flow in the transonic regime.

Work on grid fin aerodynamics has long been an attraction for researchers. The fins were introduced by the Soviets in 1980s to provide enhanced dynamic stability and control capability. They used grid fins on the SS-12 ‘Scaleboard’, SS-20 ‘Saber’, SS-21 ‘Scarab’ and SS-23 ‘Spider’ short-and intermediate-range ballistic missiles; SS-25 ‘Sickle’ mobile intercontinental missile; and 91ER1 underwater-launched antisubmarine ballistic missile. These fins have also been used on Russian spacecraft including the N1 lunar rocket and the Soyuz TM-22 capsule where they were used as emergency drag brakes. The most recognized use of grid fins however is on the Russian AA-12 'Adder' medium-range air-to-air missile. The fins are not so common in the West, but can be seen on the Massive Ordinance Air Blast (MOAB).

The aerodynamics of grid fins has been under investigation since 1985 by the US Army Missile Research and Development Center (MRDEC) [5]. However, the first known CFD calculations on grid fins were sponsored by the Defence Research Establishment Valcartier (DREV), Canada [6]. The study, limited by computational power, was based mainly on inviscid simulations with reasonable results.

Now with better and much powerful computational resources, it has become possible to run simulations giving more realistic and accurate results. This however, is the first time in Pakistan that this research has been carried out.

The current investigation involves the Navier-Stokes simulations of a standalone grid fin and compares them with that of a conventional planar fin to check for better control effectiveness. Validation of results is made by comparison against wind tunnel data and analytical results.

2 Numerical Approach

CFD analysis was carried out on a stand-alone grid fin and a conventional fin to calculate the aerodynamic parameters. Fluent® [13] finite-volume based CFD code [13] along with its preprocessor Gambit® [14] were used in the present study. The three-dimensional compressible Reynolds-Averaged-Navier-Stokes (RANS) system of equations, with appropriate turbulence model and variable property air as fluid, was solved using the coupled-implicit formulation of Fluent®. No-slip velocity boundary condition [8] was enforced at the surface of the fins. Static pressure, temperature and Mach number were specified at the farfield corresponding to the flow conditions being computed. Since the thermal problem was not of paramount importance in the present study, therefore all the surfaces were modeled as thermally insulated [8]. The CFD software package used in the present study (Fluent®8.13) is well established in CFD community and the accuracy of its results has been verified for a number of complex problems [8].

2.1 Geometry Definition

The geometry for the grid fin was selected from the work done by P. Theerthamalai and M. Nagarathinam [4]. This geometry was then non-dimensionalized according to the dimensions of the AA-12 'Adder' giving a fin with a height (h) of 200 mm, a width (w) of 100 mm and a chord (c) of 35 mm. The thickness of the plates in the lattice structure was 0.75 mm (Fig. 1). A grid fin of exactly the same size was also manufactured for conducting wind tunnel tests. A planar fin with similar dimensions as that of the grid fin was made from an ideal supersonic airfoil having a wedge angle of 10^o with c=100 mm and h= 200 mm (Fig. 2). Both the fins were modeled in Gambit®14.

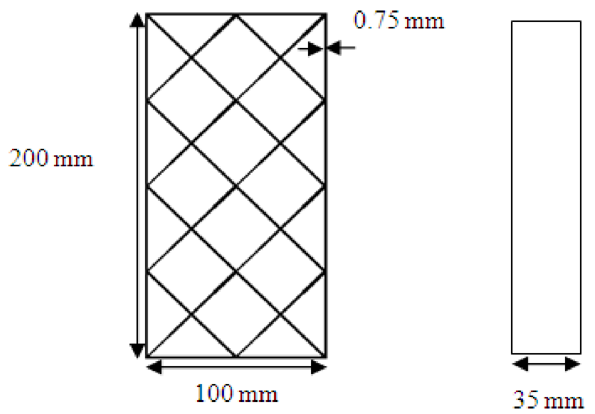

Fig. 1. Geometry of Grid Fin

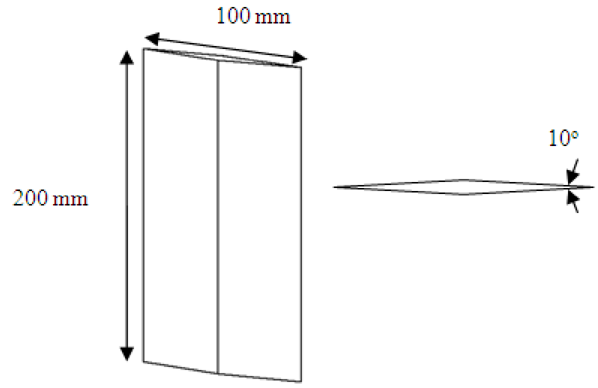

Fig 2. Geometry of Conventional Fin

2.2 Mesh Generation

For mesh generation, two separate domains were created, one enclosing the other. The inner domain was closer to the fin to control the mesh density in a better way. Moreover, the domains were broken down into smaller volumes to achieve the above said purpose more effectively. The mesh generated was a hybrid one, consisting of both structured and unstructured mesh types. Three meshes having 1.1 million, 1.3 million and 1.5 million cells were checked for mesh stability. The difference in aerodynamic parameters between the 1.3 million and 1.5 million meshes was less than

2% and pressure distribution for the two meshes was also consistent. Therefore, the mesh with a total of 1.3 million cells was selected which had 0.7 million cells for the inner domain and 0.6 million cells for the outer one. For the planar fin, a structured mesh was generated with a total of 0.77 million cells. The value of y+ for mesh with 1.3 million cells remained below 400 for all computations. Representative grid fin surface mesh is shown in Fig. 3.

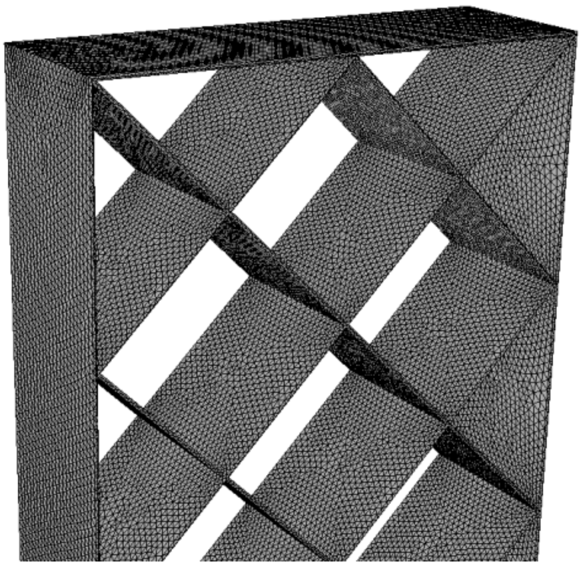

Fig. 3. Mesh Generated on the Grid Fin Surface

2.3 Flow Conditions

The simulations were carried out on the Fluent solver at M= 0.5, 0.9, 1.5, 2.0 and 2.5 at several angles of attack: 0^o, 5.73^o, 10^o, 15^o, 20^o for both the conventional fin and grid fin. Implicit, coupled solver was used. Spalart-Allmaras [7] one-equation turbulence model was selected for the calculations. This model was selected as it was relatively simple and designed specifically for aerospace applications involving wall bounded flows [8]. Moreover, previous researches also showed this model to give good results for similar flows. Keeping the mesh fine near the body helped reduce the computational requirements. Second-order discretization was used for the flow variables and viscosity was modeled to follow Sutherland behavior for supersonic flows [8].

3 Results and Discussion

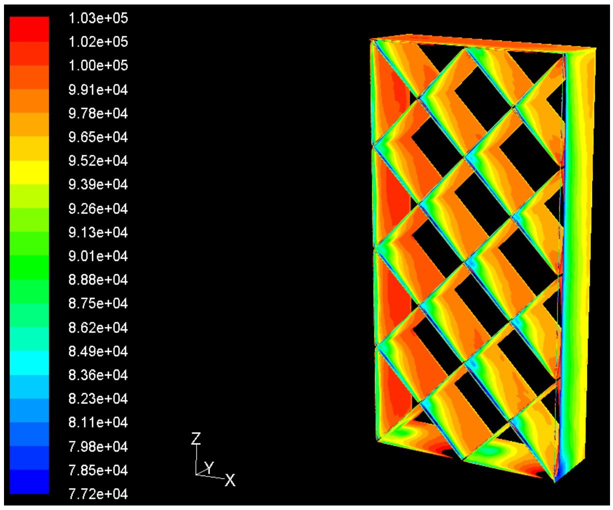

Fig. 4. Pressure Contours at M=0.5 and 10 deg AOA

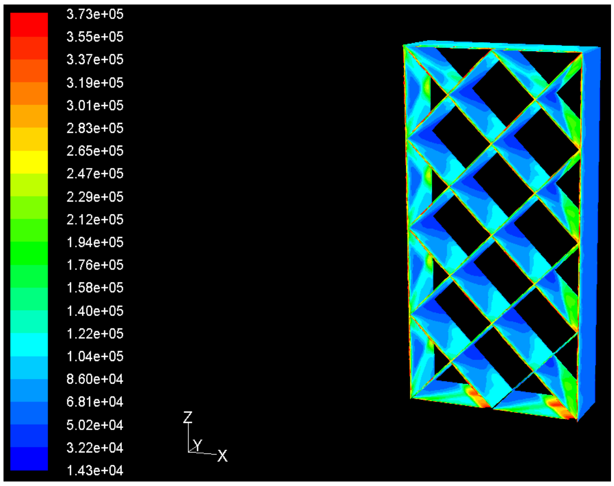

Fig. 5. Pressure Contours at M=2.5 and 10 deg AOA

The basic flow field around the pitot tube for all the cases of the present study consists of free stream flow being modified by the presence of the fins. At supersonic Mach numbers, the flow in the vicinity of the fins (planar or grid) adjusts through shock and expansion waves. The computed pressure in the vicinity of the grid fins shown in Fig. 4 and Fig. 5 for the free stream Mach number of 0.5 and 2.5, respectively. Large pressure changes at supersonic speeds due to the shock and expansion waves are evident. The integrated aerodynamic coefficients based on similar pressure distribution and wall shear stress are discussed later in this paper.

The main aim of the research was to see the control effectiveness and advantages/disadvantages of the grid fin over the conventional planar fin. Lift, drag, lift to drag ratio and hinge moment were the main aerodynamic parameters under consideration. The results showed that the major advantages which grid fins offer over the conventional fin are in the supersonic regime. The performance of the grid fin increases form low supersonic to high supersonic speeds, making them popular for use on air-to-air missiles. At early supersonic speeds, shocks which are formed inside the grid fin on each thin plate interact with each other decreasing the efficiency. As the speed keeps on increasing, the angle of the oblique shock decreases to an extent that the shock wave is swallowed through the fin increasing its control effectiveness considerably compared to a planar fin. Flow field shows that separation region for the grid fin at even Mach 2.5 and 20^{o} angle of attack is small, making it more capable to maneuver a missile at higher angles of attack. This as seen from the results is mainly due to the cascade effect [9] of the grid lattice on local aerodynamics.

The most significant advantages which make the grid fin more control effective than the planar fin were seen to be lower control force/hinge moment and high lift to drag ratio at higher angles of attack. The maximum difference in the hinge moment for the two fins at Mach 0.5 was only 2 N-m (Fig. 6), at Mach 0.9, 11 N-m and at Mach 2.5 it climbed to 27 N-m (Fig. 7).

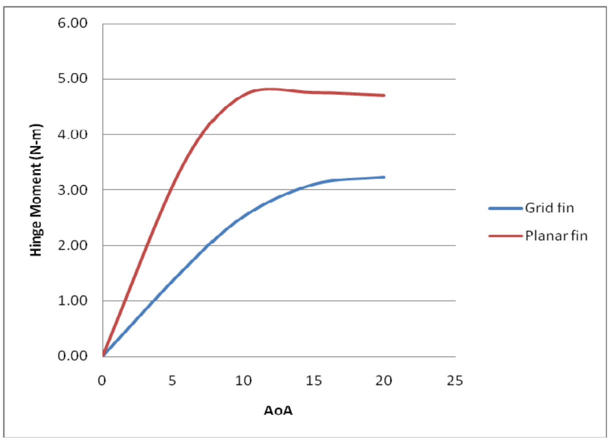

Fig. 6. Hinge Moment Vs AOA variation at M=0.5

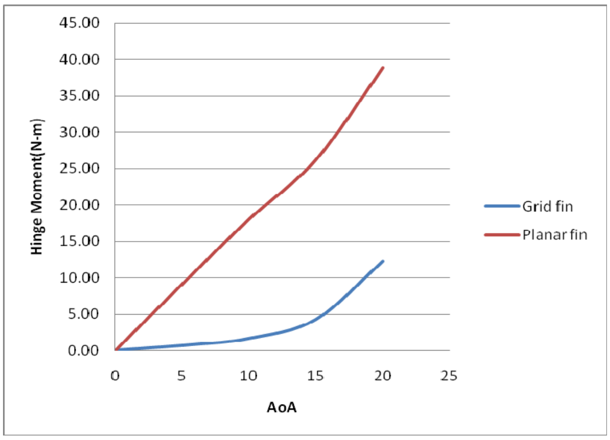

Fig. 7. Hinge Moment Vs AOA variation at M=2.5

This is an interesting trend at Mach 2.5 which shows that it requires only 12 N-m to deflect the grid fin at 20^{o}, whereas for similar conditions, the planar fin requires about 39 N-m, more than three times the force. Therefore it is much easier to turn the grid fin at higher speeds than the planar fin thus increasing the control capability of the missile.

Better lift to drag ratio of the grid fin at higher values of C_l (lift coefficient) makes it possible to maneuver at higher angles of attack. At Mach 2.5, for higher values of C_l than 0.6, the grid fin performs better (Fig. 9). Similarly, for Mach 0.5 this value is 0.76 (Fig. 8). This as mentioned earlier is due to the cascade effect of the grid lattice [9].

Other parameters like lift and drag showed the expected behavior. The lift produced by the grid at all Mach numbers was much higher than the planar fin except when there was shock interaction inside the grid fin. At that point there was a considerable drop in C_L. Once the shocks had been swallowed and the speeds reached high supersonic, the lift regained its previous trend. Drag was the major disadvantage. Grid fin produced higher drag than the planar fin for all cases. The results are shown in Figs. 10 and 11.

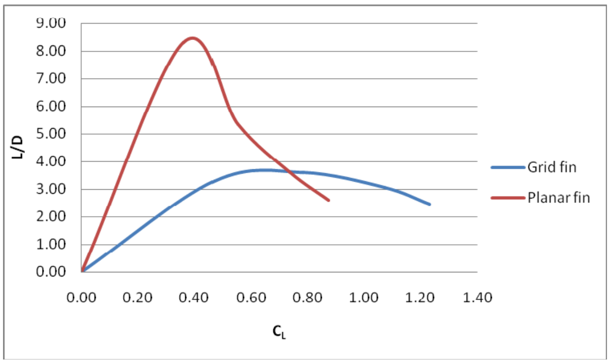

Fig. 8. L/D Vs C_L variation at M=0.5

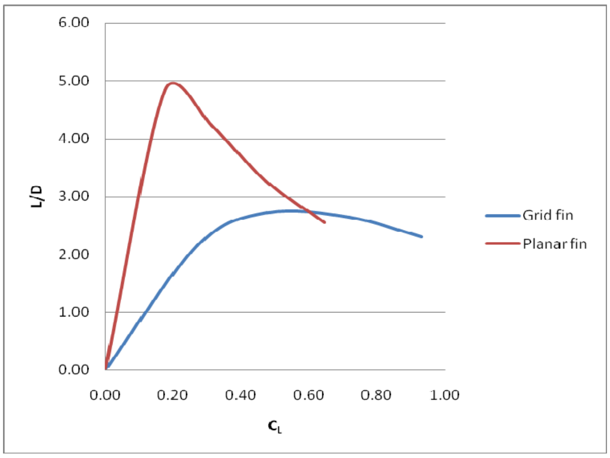

Fig. 9. L/D Vs C_L variation at M=2.5

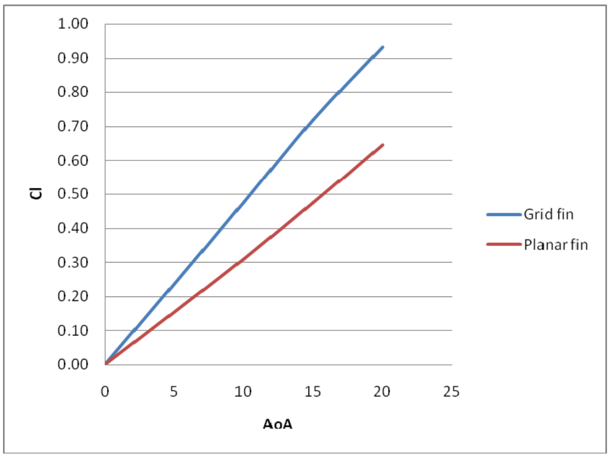

Fig. 10. C_l Vs AoA variation at M=2.5

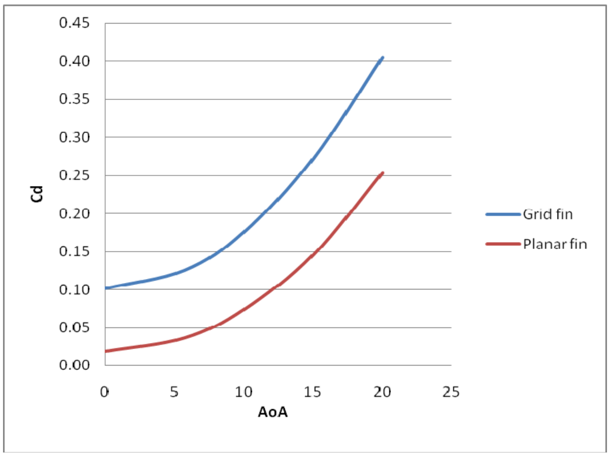

Fig. 10. C_d Vs AoA variation at M=2.5

4 Conclusion

The research concluded that the grid fins performed better at high Mach numbers and high angles of attack than the conventional planar fin. Moreover, they had the advantage of lower hinge moment and higher lift. The lower hinge moment also led to the use of smaller servo motors hence reducing the size of the tail assembly. These performance parameters showed better control effectiveness of grid fins on air-to-air missiles, as a missile usually flies at high supersonic speeds. The size of the grid fin can also be reduced to compensate for the higher drag. The size can be reduced in such a manner that the control force/hinge moment which was very low for the grid fin may be kept in a specific range to maneuver the missile effectively.

Acknowledgements

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