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CFD Analysis of Grid Fin Application on Missile in Supersonic Flow Regime

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Abstract

This research paper gives outcome of a study demonstrating a methodology for adopting computational fluid dynamics simulation to study the aerodynamics for ballistic missile with lattice fins and conventional fins at different flow regimes like subsonic, supersonic and transonic flow regimes. A grid fin or lattice fin is normally unusual control surface which is composed of an external frame supporting an internal grid of planar intersecting surfaces having small chord length. Simulations are performed for a series of Mach number values and freestream angles between 0 to 25 degree for the lattice fin as well as the conventional planar fin. Modeling of unconventional grid fin missile and conventional planar fin missile is done in CAD software called Pro-Engineer Wildfire. The meshing of geometry is done using the pre- processor named Ansys ICEM-CFD. Further, the solving and post processing is done in Solver and Post-processor called Ansys-CFX/ CFD-Post. Close conformity in results were seen for both the cases. The simulation is also giving good results for the flow structure calculations within the region of the fin for the higher freestream angles. The results were also close in predicting the flow behaviour over the individual grid fins subjected under subsonic and supersonic regimes. Thus, the enhanced aerodynamic characteristics and control effectiveness of grid fins can be observed unlike the conventional fins. Grid fins produce much higher pitching moments and lift forces to overcome the drag forces, which are produced due to higher angle of attack. The missile with grid/lattice fin arrangement generates greater normal force at diverse angles of attack than compared to the planar fins. The force along the axial direction of the grid/lattice fin missile arrangement was about 0.8 times higher than the planar fin missile.

Keywords: CFD, Missile, Grid fin, Aerodynamics.

Introduction

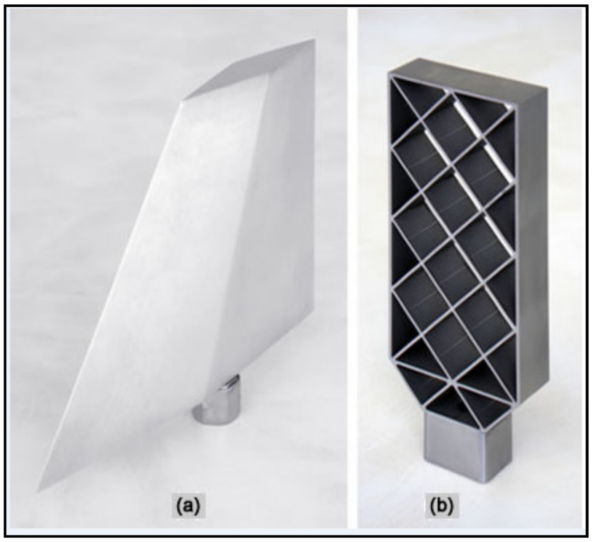
Lattice fin is unusual control and lift surface with a paneled arrangement of flow channels something like a honeycomb shaped structure. The reason for choosing grid fins over conventional fins is mainly due to its good performance at higher Mach number and freestream angles. The major disadvantage of the grid fin being choking of flow and high drag in the transonic regime.

The small chord of grid fins makes them less likely to stall at higher angle of attacks, permitting for agile turns in missile. Grid fins perform good at supersonic and subsonic speed, whereas at transonic speed the performance of the grid fin is drastically reduced. The air flow induces a normal shockwave to form within the lattice, provoking the flow to pass wholly around the fin body producing a significant amount of wave drag. However at higher Mach number values, the grid fin flow is completely supersonic and will provide lesser drag and higher control than planar fins[1].

Grid Fin Application on Missile

A grid fin which resembles a rectangular box which is full of lattice structure. The grid is made by small planar surfaces which are intersecting to create each cells which are in the shapes of either triangles or cubes. This box arrangement is quite rigid and allows the lattice walls to be very small and thin, and also decreasing the weight of the materials and in turn making it cheap for production. A grid fin or lattice fin is arranged in a perpendicular order allowing the freestream air to pass through cells of the lattice grid but to the conventional fins and are parallely aarranged to the freestream air direction[2]. Perhaps, at present the most well-known appearance of grid fin is on Russian medium range air to air missile called AA-12 'Adder'[3].

Grid fin missile and its characteristics: After launching the missiles reach the high supersonic speed. The grid fins are most attractive within this speed regime. But the main drawback of the conventional or planar fins is the long and wide surface. Apparently due to this, it is very difficult to move or turn them at a high speed, due to the forces induced by mass and quantity of air passing through it. The missile fins are turned by using servo mechanisms. This rotates and turns the fin to a new deflection angle. The magnitude of torque taken to turn the fin about its rotation axis dictates the size of servos. The bigger and huge size of conventional or planar fins makes their centre of pressure to move over a larger vicinity. This movement ultimately leads to larger hinge moment, which acts as measure of amount of torque taken to rotate the fin to a newer position[4].



Source: National University of Singapore

Figure-1
(a) Conventional planar fin, (b) Grid fin

The grid fins are shorter in the free stream direction than compared to the conventional or planar fins. These act as an advantage and result in generating smaller hinge moments. As a result, the grid or lattice fins need smaller size servos to turn them in a high speed air flow. The grid or lattice fins have a smaller length of chord making them less prone to stall at higher angle of attacks. And as compared to the conventional or planar fins, the avoidance to stall improves the control and effectiveness of the grid or lattice fins. Even though, it can be an advantage or disadvantage based on the free stream velocity. Another prominent aerodynamic parameter of the grid or lattice fins is drag. The drag is often not higher than a conventional or planar fin due to the thin dimensions of the lattice walls which generates very less perturbation in the air flowing through. Grid fins perform relatively to a planar fin at low subsonic speeds. In this speed regime the control effectiveness and drag of the lattice or grid fin, both are almost the same as that of conventional or planar fin[5]. This phenomenon does not hold true at higher subsonic number which are around Mach 1. The drag increases considerably and due to the formation of shock waves the fins become less efficient at transonic regime. The air of freestream through the cells of the grid or lattice fin can be increased to supersonic regime which effects in normal shock waves creation within the grid although, the missile may be flying below Mach number 1. This action and behaviour is often called as choked flow that blocks freestream air from going through and hence, rise in drag. The drag then later on amplifies worse for a missile flying a little faster than Mach number 1 since detached normal shock waves, which is also known as a bow shock, and it can be formed at the front of fin. But this bow shock deteriorates the effect of the choked air flow by just urging extra air to wash around the fin, thereby further increasing the drag force and decreasing the control and effectiveness.

This situation improves approximately Mach 0.8 to 1.3, as the missile hastens beyond the transonic flow regime. The normal shockwave is "swallowed" at higher speeds and shockwaves are produced apart off to the leading edge of the grid or lattice at an oblique angle. But at low Mach numbers the oblique angle is still fairly large which leads the shock waves to rebounds off the downstream lattice framework. Shock waves in large quantities inside the grid or lattice fin result in higher amount of drag which is created by these reflections. As the Mach number increases, the lesser the oblique shock angle becomes until the shock wave passes through the framework without intersecting. The drag force is caused to decrease by this behavior. But the drop cause with effectiveness and control increas compared to a planar or conventional fin[6]. Though these missiles fly at the slow speeds, the basic merit of lattice or grid fins is seen to be storage rather than lower drag force or increased control and effectiveness[7].

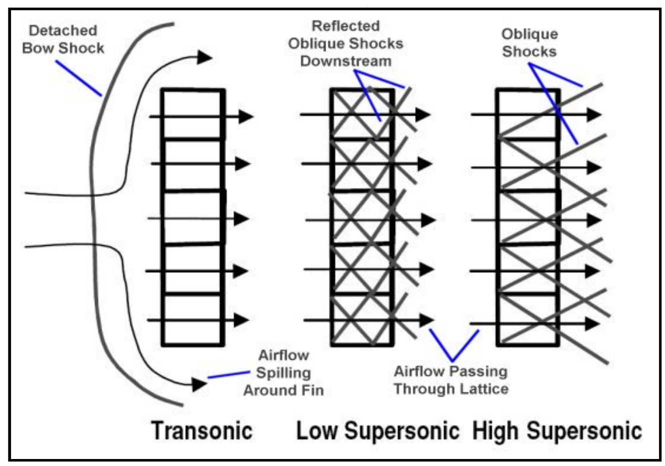


Figure-2
Flow through a grid fin at transonic and supersonic speeds[8]

At subsonic and supersonic speeds, grid or lattice fins perform good but at transonic flow regimes they do not perform well. A normal shockwave caused by the flow to form within the lattice, which results in a significant amount of the air to flow completely over the fin instead of within it and producing enough wave drag. However, at higher values of Mach number, the grid or lattice fins have a complete supersonic flow providing less drag force and also a greater control and maneuverability compared to planar or conventional fins.

CFD Analysis of Grid Fin Application on Missile in Supersonic Flow Regime

It is possible to run simulations yielding more accurate and realistic results at present with better and more powerful computational resources. The Navier Stokes simulations of a grid or lattice fin are involved in the current investigation and to check for better control effectiveness differentiates them with the conventional or planar fin.

Geometry and Mesh Generation: By using Pro-Engineer Wildfire 4.0 the CAD geometry models of the conventional planar fin missile and grid fin missile was generated. By using the preprocessed, Ansys-ICEM the unstructured mesh for two configurations were constructed, and later on supplied in the Ansys-CFX software suite.

As per the dimensions of a ballistic missile having a fin width (w) of 100 mm, a height (h) of 200 mm, and a chord length(c) of 35 mm. The geometry of fins considered was non-dimensional. The dimensions of the fin model are represented in the picture below.

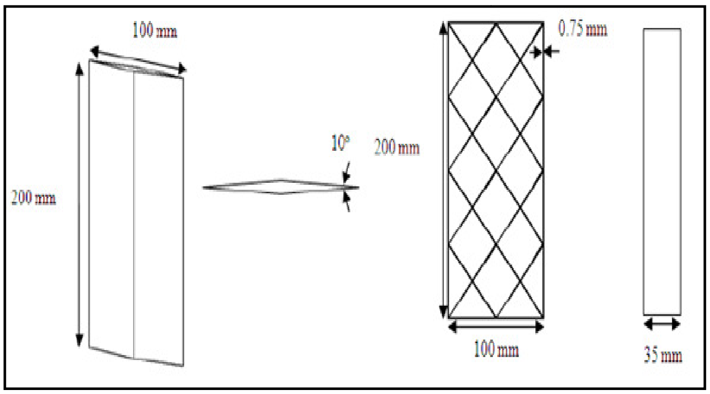


Figure-3
Geometry of Conventional Fin and Grid Fin

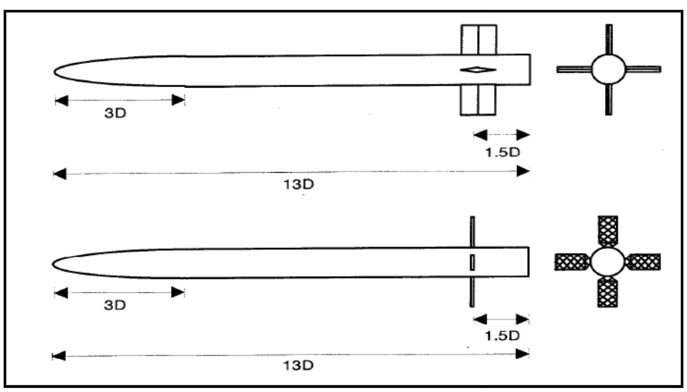


Figure-4
Design Configuration of Missile

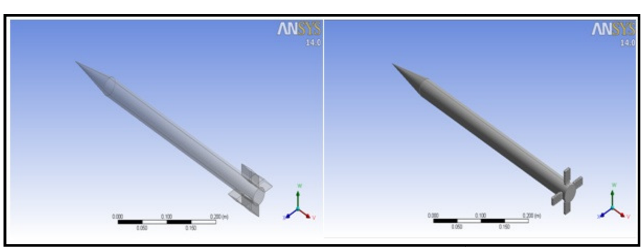


Figure-5
Conventional and Grid Fin Missile Geometry modelled in Pro-E

In order to generate an unstructured mesh a circular domain is chosen around the missile configurations. Fine mesh over the boundary layer was used on the missile body and fin surface. The domain was composed of pyramid and tetrahedrons elements. At upstream end, the surface was modeled with triangular mesh. The meshes were conformal between volumes, or matching exactly at boundary surface.

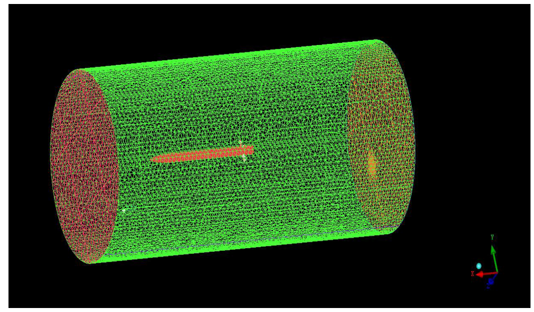


Figure-6
Mesh generated on the Circular Domain of missile

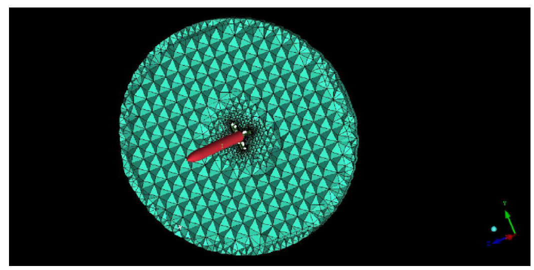


Figure-7
Sectional view of mesh generated on Grid fin missile

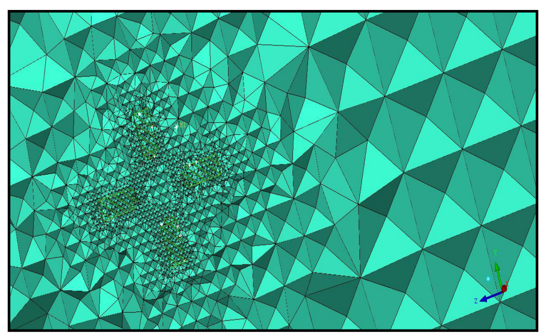


Figure-8
Mesh around grid fins

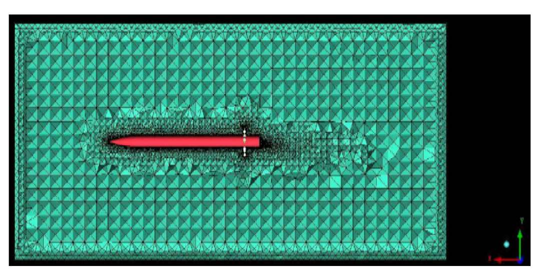


Figure-9
Side view of mesh generated for Grid Fin Missile

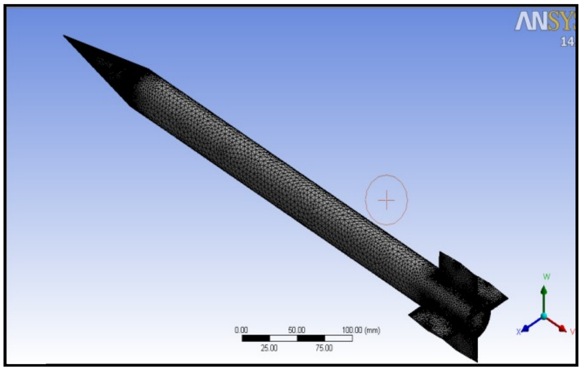


Figure-10
Mesh generated for Conventional Planar Fins Missile

By checking criteria like quality, aspect ratio etc the quality of meshing was found satisfactorily. By using the tetra meshing feature of ICEM-CFD a three-dimensional unstructured tetra grid (mesh) has been generated. The mesh size is 2 million cells in each case. By using prism cells the grid is refined in the near wall regions. As the tetrahedral elements are unstructured and requires less time to complete are used for easy meshing. Then the mesh file is exported to suitable solver.

Flow Parameters: Steady state solutions were made to predict the airflow for three mach number cases using CFD software, Ansys CFX. CFX is a general purpose Computational Fluid Dynamics (CFD) software, combining an advanced solver with pre processing and post processing capability. The next generation physics pre-processor, CFX Pre; allows more number of meshes to be imported and every portion of complex geometry to use the most appropriate mesh.

The simulations were performed in solver at M = 2.5 and several angle of attack namely: 0, 5, 10, 15 and 20 degrees for both the cases. Spalart Allmaras model[8], which is one equation turbulence model was used in these calculations. The modified version of Spalart Allmaras model[8] was used in order to accommodate the wall function and to resolve the viscous-affected in case the mesh refinement is not sufficiently fine near the wall region of the boundary layer. The computational requirements were decreased as much as possible and this capability was adopted in generating the mesh.

The inlet boundary condition was applied as free stream velocity boundary condition and for outlet condition the static pressure was taken to be zero. A non slip smooth wall boundary condition was used for all solid surfaces. For missile body and other parts of flow domain, adiabatic wall boundary condition with no transfer of heat is considered. In the present study the thermal solution was not of significant importance. Therefore, all the surfaces are modeled to behave as thermally insulated. The static temperature across the domain was assumed to be 300 K. The y+ value and Reynolds number for the missile bodies is presented in Table I. It takes about 1000 iterations to converge, with the residual factor reduced to 10^{-10}.

Table-1
Wall y+ value Details

Freestream Velocity (m/s)	Reynolds Number	Estimated Wall Distance or Initial Height (m)	Total Height (m)	Number of Layers
850	1.3e+9	6.8e-7	0.003189	26

Results and Discussions

Coefficient of Lift (C_L) v/s Angle of Attack: A better lift and lower drag for the grid fin at higher values of C_L makes it possible to control at higher angles of attack. At Mach number 2.5, for higher C_L values than 0.6, the grid or lattice fin performs well. This is because of cascading effect of the grid lattice.

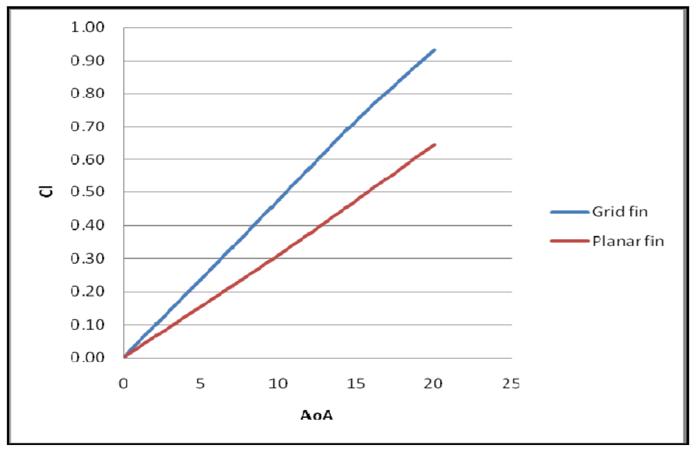


Figure-11
C_L v/s Angle of Attack at M = 2.5

In case of shock interaction inside the lattice fin, the lift generated by the grid fin in every case was much more than that in planar fin. At that point there was a considerable drop in C_L. The lift regained its previous trend once the shocks had been absorbed and the speeds reached high supersonic,

Pressure Contours: At high mach numbers of supersonic flow, the flow in the surrounding area of fins (conventional or lattice fins) adjusts through expanded and shock waves. The magnitude of pressure which is computed in the surrounding region of the grid or lattice fins shown in Figure 3.10. For the free stream Mach number 2.5, high pressure changes are evident at supersonic speeds due to the expansion and shock waves.

Mach Number Contours: The colour of contour differs from portion to portion, where green colour depicts the air velocity at the inlet section. The maximum velocity or acceleration due to presence of fins and the missile were seen in the leading edge (yellow color at front portion) and the ones having maximum velocity decelerations are indicated on trailing edges (bluish color at backside) as depicted in Figure-14.

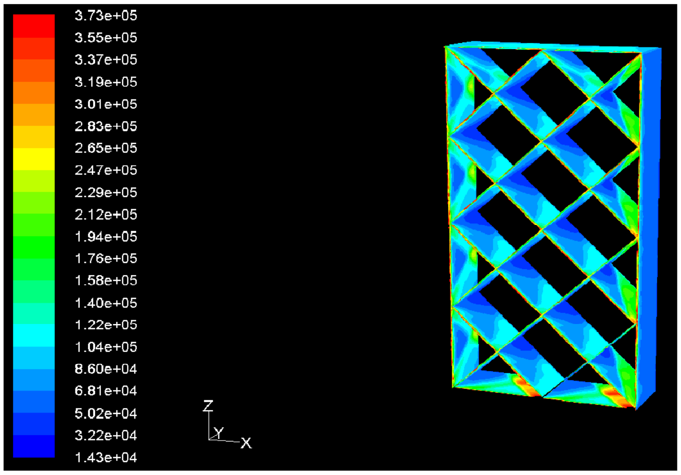


Figure-12
Pressure Contours around a Grid Fin at M = 2.5

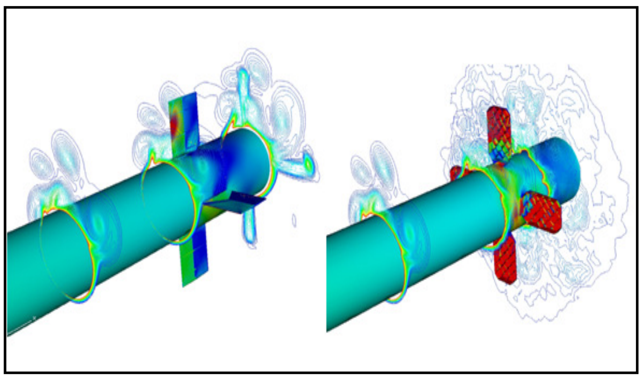


Figure-13
C_P contours of conventional and grid fin missile at M = 2.5

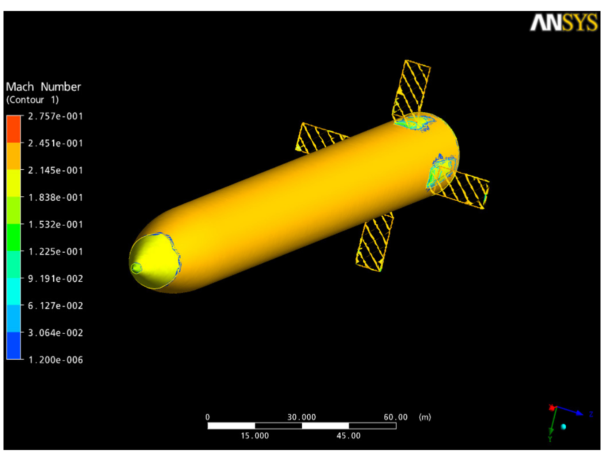


Figure-14
Mach number contours on grid fin missile at M = 2.5

Streamline Plot: To represent the flow visualization at various angle of attack, streamline plot is drawn along the missile body with grid or lattice fin. It is observed that the TEV (Trailing edge vertex) is induced in the trailing edge for missile body framework, as shown in figure.

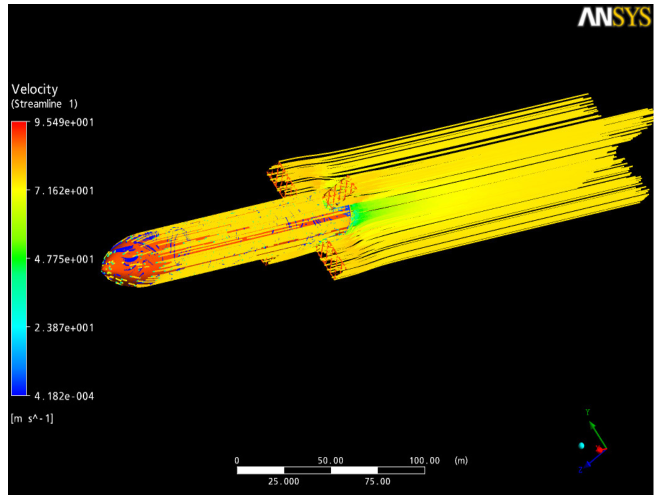


Figure-15
Mach number contours on grid fin missile at M = 2.5

Conclusion

Using CFD simulation, calculations of viscous flow past a missile with grid or lattice fins was made for mach number of 2.5 and several angles of attack. The results were validated by comparing it to the simulated aerodynamic coefficients for the grid finned missile and conventional fin missile. For all configurations investigated, a very good agreement with measured data was noticed. The viscous variable of axial force on the lattice fin is about one and a half times more than that on the conventional fin. The net axial force component on grid or lattice fin was 2 to 3 times higher than that in planar or conventional fin. The missile body with grid or lattice fin arrangement generates greater normal force coefficients at higher angles of attack and the behaviour seems to be increasing continuously for higher mach number. The axial force component over the grid or lattice fin missile body is around 0.8 times more than that in planar or conventional fin. It is also noticed from the computations performed using computational package, that grid or lattice fins induce a positive vector of normal force coefficient at zero degrees angle of attack whereas planar or conventional fin do not have such characteristics. The axial force component for the grid or lattice fin arrangement is slightly higher than that in planar or conventional fin arrangement. Hence, it can be concluded that grid fins produce less drag force and greater control or maneuverability than planar or conventional fins at supersonic speeds.

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