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Study of Swept Angle Effects on Grid Fins Aerodynamics Performance

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Abstract. Grid fin is an aerodynamic control surface that usually used on missiles and rockets. In the recent several years many researches have conducted to develop a more efficient grid fins. There are many possibilities of geometric combination could be done to improve aerodynamics characteristic of a grid fin. This paper will only discuss about the aerodynamics characteristics of grid fins compared by another grid fins with different swept angle. The methodology that used to compare the aerodynamics is Computational Fluid Dynamics (CFD). The result of this paper might be used for future studies to answer our former question or as a reference for related studies.

Key Words: Grid Fin, Swept-Back, Lattice Fin, CFD Simulation.

1. Introduction

A Grid fin is an aerodynamic control surface that usually used on missiles and rockets (see Figure 1). Unlike the conventional planar fins, grid fins consist of an outer frame with internal lattice of intersecting thin walls with small chord instead of using single body supersonic airfoil (see Figure 2). The mounting of grid fins and conventional planar fins also different, unlike the conventional planar fins that aligned parallel to the direction of airflows the grid fins mounted perpendicular with the airflows.

Figure 1 Grid Fins mounted on SpaceX Falcon 9 Rocket, source: https://i.stack.imgur.com/rnHbB.jpg
According to Marco Debiasi:

The main advantage of grid fins is that they have significantly smaller chord than conventional planar fins. Thus, they generate smaller hinge moments which require smaller actuators to rotate them in a high-speed flow. Their small chord also makes them less likely to stall at high angles of attack which increases their control effectiveness compared to conventional planar fins.

Another advantage of grid fins is that they can be folded easily against an aerodynamic body to make them more compact and convenient to store or transport. [1]

Zubair Khan Kittur and Amit Bahekar [2] wrote on their paper that grid fin is very efficient compared to planar fin in supersonic flow, but it’s not efficient in transonic flow. When grid fin in transonic flow, it produces shockwaves at the front of the grid fin, this blocks the freestream air going through the lattice and produce a high amount of drag. This statement also written by Salman Munawar [3] in his paper.

The other advantage of grid fin instead of planar fin is the stall angle of grid fin is very high. William D. Washington and Mark S. Miller [4] have conducted experiments of grid fin and the result was the grid fin did not stall at angle of attack of 30-degree.

There are many variations of grid fins design and one of them is the variations of swept angle. The use of swept angle on a grid fin either it’s swept back or swept forward might improve the aerodynamics characteristics. Actually, there are many variations in grid fin geometry besides swept angle variations. But, this paper will only discuss about the effects between the aerodynamics characteristics of a grid fin and the swept angle on a grid fins. The aerodynamics characteristic that will be measured on this paper are drag coefficient, lift coefficient, and moment coefficient.

The method that will be conducted in this research is computational fluid dynamics (CFD). Computational fluid dynamics is able to simulate the fluid flow inside the lattice grid and also the fluid flow around the grid fin. DeSpirito and Sahu [5] have conducted research about viscous CFD calculations of grid fin using FLUENT. The result they obtained led to good agreement between the CFD data and aerodynamic coefficients measured by experiments. The geometries that will be evaluated to obtain aerodynamics coefficient are base configuration, swept back with 5°, 15°, 20°, and 30° angles, and forward swept with 5°, 15°, 20° angles.
To measure the aerodynamics performance criteria the magnitude of lift coefficient, drag coefficient, and pitching moment coefficient must be known. These coefficients can be calculated from force and moment obtained from CFD simulation. To determine which is the best configuration, the ratio between lift coefficient and drag coefficient (Cl/Cd) was used. The value of Cl/Cd indicates aerodynamic efficiency of an object. In other words, bigger Cl/Cd value is desired.

The main objective of this study is to compare the aerodynamics characteristics between grid fins with different configuration on its swept angle. It’s expected that the variations in swept angle could improve the aerodynamic characteristics and the efficiency of the grid fins.

2. Geometry Configurations
The grid-fin geometry used in this study was based on the geometry that used by Zubairkhan Kittur 2, but with some modifications. All the dimensions that used in the geometry are relative to the spacing of the grid. Later we can define the spacing as “s”. The width of the grid-fin is 2s, the length of the grid fin is 3s, the height of the grin fin is 0.625s, and the swept angle Λ. For this case, we have the value of s is 80 mm and Λ is 30 degree, therefore we have the dimension of the grid fin as stated in figure 3 below.

![Figure 3 Schematics of the grid-fin with 30 degree swept back configuration](image)

3. Numerical Approach
In this study, the methodology that will be conducted is numerical simulation using computational fluid dynamics (CFD). Computational fluid dynamics is able to simulate the fluid flow inside the lattice grid and also the fluid flow around the grid fin, moreover this method provide the detailed flow fields including pressure contours and integrated aerodynamic coefficients [6]. ANSYS CFX will be used as the solver of CFD simulations. This solver software is based on Reynolds Averaged Navier-Stokes (RANS) method. This method was chosen because it delivers enough accuracy and faster processing rather than Large Eddy Simulation (LES) method that has higher accuracy but it takes a lot of memory and running time [7].
RANS or Reynolds Averaged Navier-Stokes equations are the simplified form of the Navier-Stokes equations. These equations are simplified by separating the flow variables into the time-averaged components and the fluctuating components using Reynolds Decomposition. However, in order to achieve a good accuracy in turbulence flow modelling RANS equations need turbulence model equations. K-ε turbulence model were chosen to solve turbulence flow problems in this simulation. K-ε turbulence model is a two-equation model, that means this turbulence model adds two extra transport equations to represent the turbulence flow. This turbulence model is one of the most common turbulence model.

The CFD model have a quadrilateral prism domain with a perpendicular downstream boundary located 9.375s away from the main object, a perpendicular upstream boundary located 6.25s away from the main object, three slanted upstream boundaries, a symmetry boundary located on the grid fin’s main arm root, and non-slip wall type for all solid surfaces. The boundaries were arranged to make analysis with multi angle of attack easier. The meshing type that will be used in this simulation are tetrahedrons and prisms. Tetrahedrons and prisms were chosen because grid fins geometry has so many acute angles that will be difficult to cover with hexahedrons meshing type.

The number of mesh elements in the simulation was determined by using convergence test or grid sensitivity test. The test was done by adding the number of mesh elements until the drag coefficient in base configuration with alpha 0 reaches difference of 5 drag counts. Figure 6 below shows us that the number of mesh elements is about 3.5 million.

![Figure 4 Boundary Conditions at the Domain: front view (left), side view (right)](image)

![Figure 5 Mesh arounds the grid fin.](image)
Figure 6 Grid Sensitivity Test.

In this simulation, the conditions were assumed that the grid fin is at the 10,000 meters ASL with ISA condition and the freestream speed is Mach 1.5. This conditions were chosen to represent the “actual” conditions of a missile with Mach 1.5 at the 10,000 meters above sea level. But, then again this “actual” conditions are just the writers’ assumption.

After running the analysis. The lateral force, axial force, and the pitching moment can be measured using CFD-Post software. The lateral force represents the lift force and the axial force represent the drag force. In this case, lift force shows us the capability of a control surface to control the object’s main body and the drag force shows us how much loss of momentum and energy while the grid fins control the object. On other hand, pitching moment shows us how much torque to be applied to the grid fin in order to control the main body.

4. Result

Coefficient of Drag v/s Angle of Attack:
According to figure 7 below, grid fin without any swept angle or the base model has the highest drag coefficient at any angle of attack among the other model. Meanwhile the 30-degree swept back model has the lowest drag coefficient at any angle of attack among the other model. The effect of swept back or swept forward also visible on the graph. Comparing swept back and swept forward with 5,15, and 20 degrees’ angle, the swept forward configuration seems with higher drag coefficient than the swept back configuration with the same swept angle.
Figure 7 Graph of Drag Coefficient v/s AoA at Mach=1.5

Table 1 Drag Coefficient v/s AoA at Mach=1.5

| Swept\alpha | 0       | 3       | 6       | 9       | 12      | 15      |
|-------------|---------|---------|---------|---------|---------|---------|
| -20         | 0.117270768 | 0.1271460 | 0.1567480 | 0.2015260 | 0.262950 | 0.3378440 |
| -15         | 0.119459823 | 0.1298950 | 0.1602970 | 0.2067980 | 0.2696350 | 0.3458250 |
| -5          | 0.120397989 | 0.1320130 | 0.1642670 | 0.2119570 | 0.2762130 | 0.3556920 |
| 0           | 0.130905450 | 0.1424360 | 0.1730390 | 0.2123860 | 0.2789370 | 0.3616020 |
| 5           | 0.119459823 | 0.1311180 | 0.1638310 | 0.2123860 | 0.2789370 | 0.3616020 |
| 15          | 0.116019880 | 0.1270240 | 0.1591570 | 0.2081970 | 0.271380 | 0.3486360 |
| 20          | 0.112767571 | 0.1238330 | 0.1548710 | 0.2035810 | 0.271380 | 0.3486360 |
| 30          | 0.105324786 | 0.1145750 | 0.1429180 | 0.1906040 | 0.2544620 | 0.3268220 |

Coefficient of Lift v/s Angle of Attack:

Figure 8 shows us that the grid fin with 5 degree swept back configuration has the highest number of lift coefficient at any angle of attack between 0 to 15. Meanwhile the 30-degree swept back configuration and 20 degree swept forward configuration gives the two lowest lift coefficients among the other configuration.
Table 2 Lift Coefficient v/s AoA at Mach=1.5

| Swept\alpha | 0   | 3   | 6   | 9   | 12  | 15  |
|------------|-----|-----|-----|-----|-----|-----|
| -20        | -2.68941E-05 | 0.18651 | 0.360481 | 0.508742 | 0.667928 | 0.8121 |
| -15        | -3.70888E-06 | 0.207715 | 0.407487 | 0.570604 | 0.714984 | 0.863004 |
| -5         | -0.000129467 | 0.210614 | 0.395811 | 0.547807 | 0.703896 | 0.864923 |
| 0          | 0.000235792 | 0.212146 | 0.414702 | 0.577312 | 0.732308 | 0.886025 |
| 5          | -5.47264E-05 | 0.203342 | 0.403747 | 0.567653 | 0.735159 | 0.8789 |
| 15         | -0.000150107 | 0.172554 | 0.349168 | 0.521744 | 0.681242 | 0.809873 |

Coefficient of Pitching moment v/s Angle of Attack:
The pitching moment coefficient graph shows that at a particular angle of attack, grid fin with 30 degree swept back configuration has the most negative pitching moment. It indicates that this configuration need a motor with bigger torque to move it. Meanwhile the base model or 0 swept angle degree configuration has the most positive pitching moment among the other.

Figure 9 Graph of Pitching Moment Coefficient v/s AoA at Mach=1.5

Table 3 Pitching Coefficient v/s AoA at Mach=1.5

| Swept\alpha | 0   | 3   | 6   | 9   | 12  | 15  |
|------------|-----|-----|-----|-----|-----|-----|
| -20        | 0.00011258 | -0.09943 | -0.17325 | -0.22178 | -0.30284 | -0.38352 |
| -15        | -4.44065E-05 | -0.10073 | -0.182 | -0.23066 | -0.30034 | -0.37439 |
| -5         | -0.000132594 | -0.09439 | -0.17675 | -0.22316 | -0.27082 | -0.34037 |
| 0          | 0.000187633 | -0.08522 | -0.14123 | -0.17863 | -0.23554 | -0.30934 |
| 5          | -0.000216529 | -0.10603 | -0.19902 | -0.25406 | -0.32048 | -0.40566 |
| 15         | 0.000110078 | -0.13209 | -0.25893 | -0.34387 | -0.45808 | -0.56715 |
| 20         | 0.000162615 | -0.14235 | -0.27757 | -0.38002 | -0.50786 | -0.6287 |
| 30         | -4.62829E-05 | -0.14498 | -0.29671 | -0.43894 | -0.58492 | -0.71801 |
Aerodynamic Efficiency v/s Angle of Attack:
The aerodynamic efficiencies were determined by the ratio of lift coefficient over drag coefficient. From figure 4.4 below, the base model appears with the lowest aerodynamic efficiency at every angle of attack between 0 and 15 degrees. The highest number of aerodynamic efficiency at angle of attack up to 6 degree is reached by the 5-degree swept back configuration, meanwhile from angle of attack 9 degree up to 15 degree the 30-degree swept back configuration has the highest number of aerodynamic efficiency.

![Graph of Aerodynamic Efficiency v/s AoA at Mach=1.5](image)

**Figure 10 Graph of Aerodynamic Efficiency v/s AoA at Mach=1.5**

| Swept| 0   | 3   | 6   | 9   | 12  | 15  |
|------|-----|-----|-----|-----|-----|-----|
| -20  | 0.000229 | 1.46722 | 2.299748 | 2.524452 | 2.540132 | 2.403775 |
| -15  | 0.000953 | 1.499662 | 2.366164 | 2.572723 | 2.552515 | 2.405778 |
| -5   | 3.08E-05 | 1.573449 | 2.480635 | 2.692075 | 2.588521 | 2.426266 |
| 0    | 0.000989 | 1.478655 | 2.287404 | 2.481483 | 2.45893 | 2.351219 |
| 5    | 0.001974 | 1.617985 | 2.531285 | 2.718218 | 2.625358 | 2.45028 |
| 15   | 0.000472 | 1.600821 | 2.53678 | 2.726524 | 2.648646 | 2.463432 |
| 20   | 0.001331 | 1.594358 | 2.513659 | 2.731595 | 2.657252 | 2.462221 |
| 30   | 0.001271 | 1.506035 | 2.44313 | 2.737324 | 2.67718 | 2.478025 |

Airflow Contour
The airflow contour of grid fin with swept back, base model, and swept forward configuration are shown in figure 11 and 12 below.
Figure 11 Mach number contour plot with freestream $M= 1.5$ and AoA 0 deg on a) base model grid fin b) 15 deg forward swept c) 15 deg swept back.

Figure 12 Total Pressure contour plot with freestream $M= 1.5$ and AoA 0 deg on a) base model grid fin b) 15 deg forward swept c) 15 deg swept back.
5. Analysis and Discussion

According to the results section, the grid fin with 5 degree swept back angle has the highest aerodynamic efficiency at AoA from 0 to 6 degree, while the 30-degree swept back angle configuration has the highest aerodynamic efficiency at AoA from 9 to 15 degrees. The swept back configurations have the highest aerodynamic efficiency because of its shape that prevent energy loss caused by shockwave as much as the base model and the swept forward configuration model.

6. Conclusion

Using CFD simulation, calculation of a flow past a grid fin at supersonic speed can be obtained. The highest value of drag coefficient possessed by base model grid fin because it has greater total pressure loss than the other models. Meanwhile, at AoA from 0 to 15 grid fin with 5 degree swept back configuration has the highest lift coefficient among the other configuration. For pitching moment coefficient, the base model has the most positive pitching moment, contrary the swept back 30-degree model has the most negative pitching moment. At last, the grid fin with 5 degree swept back angle has the highest aerodynamic efficiency at AoA from 0 to 6 degree, while the 30-degree swept back angle configuration has the highest aerodynamic efficiency at AoA from 9 to 15 degrees. With these results, it can be concluded that generally, the swept back grid fin configuration is the most efficient configuration.

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