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The research analysis of aerodynamic numerical simulation of grid fin*

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Abstract: This paper presents the results of an investigation to use arc-length mesh generation and finite volume TVD scheme to calculate Euler equations for predicting the effect of geometry parameters in reducing the drag force and improving the lift-drag ratio of grid fin in the supersonic flow regime. The effects of frame and web, whose cross section shape and thickness and spacing, on the aerodynamic character of the grid fin were studied. Calculations were made at Mach 2.5 and several angles of attack. The results were validated by comparing the computed aerodynamic coefficients against wind tunnel experimental data. Good agreement was found between computed and experimental results. The computed results suggest that parameters of the grid fin's frame have the greatest effect on the grid fin aerodynamic character, especially on its drag force. It was concluded proper choice of appropriate grid fin geometry parameters could reduce the drag force and improve the lift-drag ratios.

Key words: Grid fin, Aerodynamic character, Numerical simulation
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INTRODUCTION

A grid fin is an unconventional lifting and control surface consisting of an outer frame supporting an inner grid of intersecting small chord planar surfaces. Interest in grid fin is primarily based on its potential use on highly maneuverable munitions due to their advantages over conventional planar controls at high angles of attack (α) and high Mach numbers. The fin design yields favorable lift characteristics at high α and near-zero hinge moments, which allow the use of small and lightweight actuators (Ma, 2003; Simpson and Sadler, 1998).

The aerodynamics of grid fins has been investigated since 1985 by the U.S. Army Missile Research and Development Center (MRDEC) (Washington and Miller, 1998). These investigations indicated that one of the advantages of grid fins is the ability to maintain lift at higher angles of attack since they do not have the same stall characteristics as those of planar fins. Another is the very small hinge moment, which can reduce the size of control actuator systems. Curvature of the grid fins had little effect on their performance so that folding the fins down onto the missile body is a storage design advantage. The main disadvantage was indicated to be higher drag compared to that of planar fins, although some techniques for minimizing drag by altering the grid fin frame cross-section shape were demonstrated. These studies also showed that grid fins experience a loss in control effectiveness in the transonic regime due to choking of the flow in the individual cells.

Available data on grid fins are based on wind tunnel tests (Simpson and Sadler, 1998), free-flight aeroballistic range tests (Abate *et al.*, 1999), and numerical and theoretical investigations (Sun and Khalid, 1998). Computational fluid dynamic (CFD) computations of Sun and Khalid showed reasonable

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agreement of the fin normal force with experimental data from Washington and Miller (1994). The computations of (Chen *et al.*, 2000) concentrated on the flow in the region of grid fin while studying the effect of a fairing ahead of the base of the fin. These investigations were performed in the supersonic regime, at Mach numbers of 1.5 to 2.5.

The current investigation is aimed at using arc-length mesh generation and finite volume TVD scheme for calculating Euler equations to predict the effects of its geometry parameters on the aerodynamic character of the grid fin, especially on its drag force and lift-drag ratio. The effects of frame and web, whose cross section shape, thickness, and spacing, on the aerodynamic character of the grid fin were studied. The calculations were made at Mach 2.5 and several angles of attack. This paper presents the results of these calculations and their validation against wind tunnel data (Chen *et al.*, 1999).

MESH GENERATION OF GRID FIN

Numerical computational model

This work mainly researched on the aerodynamic character of single vertical parallel honeycomb class grid fin and on the effects of different shape and thickness of frame, and of the web cross section and the web thickness on the grid fin. *IN* and *IM* refer to the numbers of vertically and horizontally bar. The geometry parameters and the configuration of the grid fin, which were researched in this work, are listed in Fig.1 and Table 1.

Arc-length mesh generation

Arc-length technique is a kind of algebra mesh generation method, which has clear geometry concept, and is easy and quick to mesh generate. Interpolation techniques are introduced, which permit a given distribution of grid points on the edges of a three-dimensional grid block to be propagated through the surface and volume grids (Wu and Zhao, 2002). The vertical honeycomb grid fin mesh is generated by arc-length method here. The grid fin mesh number is 140×110×20. It is 20 mesh cells across the grid fin web thickness, and the outer boundary is about 5 times of the grid fin width. Its section and surface mesh are shown in Fig.2 and Fig.3.

COMPUTATIONAL METHOD

The finite volume TVD numerical simulation scheme, which is deduced from the 2D TVD of Harten equations, calculated the Euler conservation

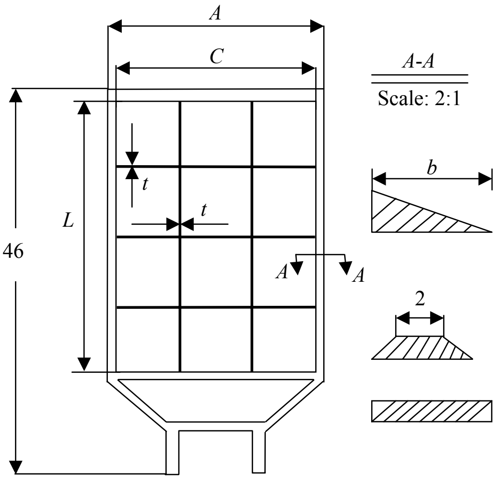

Fig.1 Configuration of vertical parallel honeycomb class

Table 1 The geometry parameters of grid fin

Parameter number	*A* (mm)	*C* (mm)	*L* (mm)	*IM* (number)	*IN* (number)	*T* (mm)	*B* (mm)	Shape of the frame cross section
GSM	22.0	20.4	30	2	3	0.15	5	⏢
GSMM	22.0	20.4	30	2	3	0.15	5	▭
GSMD	22.0	20.4	30	2	3	0.15	5	◺
GSMJ	22.0	20.4	30	2	3	0.25	5	⏢
GSMK	22.0	20.4	30	2	3	0.15	5	⏢
GSMX	22.0	20.4	30	1	1	0.15	5	⏢
GSMY	22.0	20.4	30	2	2	0.15	5	⏢

Note: GSM, GSMJ, GSMK, GSMX and GSMY are the grid fin with both sides chopped; GSMJ is the grid fin with thicker web cross section; GSMK is the grid fin with thicker frame; GSMM is the grid fin with rectangular frame; GSMD is the grid fin with one side chopped; GSMX and GSMY are the grid fins with web cross section number changed

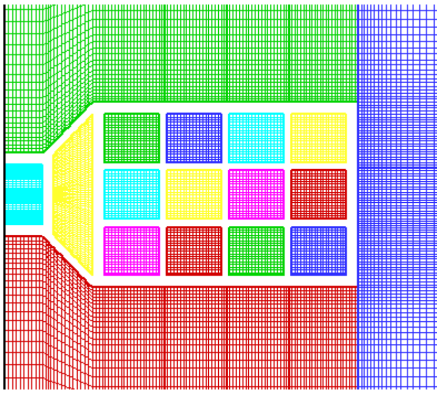

Fig.2 The grid in *y*-*z* section of grid fin

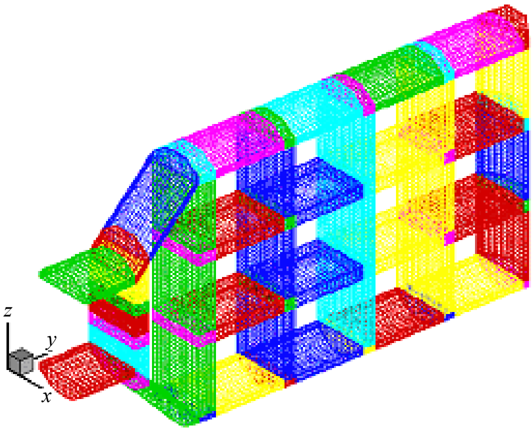

Fig.3 The grid of three-dim surface of grid fin

equation in Descartes rectangular coordinates [Eq.(1)] to simulate the 3D grid fin flowfield. Harten used the method of flux amended on single equation (Harten, 1983). The 3D Euler conservation equation can be written as three one-dimensional equations [Eq.(2)], which can be solved using splitting technique (Wu, 2003).

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial x}+\frac{\partial \boldsymbol{G}}{\partial y}+\frac{\partial \boldsymbol{H}}{\partial z}=0 \qquad (1)$$

here, $\boldsymbol{U}$ is variable, and $\boldsymbol{F}$, $\boldsymbol{G}$, $\boldsymbol{H}$ are conservation flux.

$$\begin{cases}\dfrac{\partial \boldsymbol{U}}{\partial t}+\dfrac{\partial \boldsymbol{F}}{\partial x}=0\\ \dfrac{\partial \boldsymbol{U}}{\partial t}+\dfrac{\partial \boldsymbol{G}}{\partial y}=0\\ \dfrac{\partial \boldsymbol{U}}{\partial t}+\dfrac{\partial \boldsymbol{H}}{\partial z}=0\end{cases} \qquad (2)$$

Steady-state calculations were performed at Mach numbers 2.5, and at several angles of attack: −4°, −2°, 0°, 2°, 4°, 6°, and 8°. The freedom conditions were Reynolds number of 3.84×10^6, static temperature of 187 K, and static pressure of 1.332×10^4 Pa. An outflow boundary condition was used downstream, a pressure inflow (free-stream conditions) boundary condition was used upstream, and a far-field pressure (nonreflecting) boundary condition was used for the outer boundary. A slip wall boundary condition was used for the reflecting solid surfaces.

COMPUTATIONAL RESULTS AND ANALYSIS

Computational results

This work mainly researched the effects of different shape and thickness of frame and of thickness of web and web spacing on the grid fin. Some charts of drag coefficients, lift coefficients, and pitching moment coefficients of grid fin at Mach number 2.5 are given in Fig.4 to Fig.9.

Results analysis

The grid fin drag coefficients, lift coefficients, and pitching moment coefficients vary with the angles of attack. The drag characteristics vary parabolically in Fig.4. Lift characteristics vary as a beeline through the zero point in Fig.5. The absolute value of pitching moment, whose sign is opposite, becomes larger with bigger angle of attack in Fig.6. All these implied that the fin model has static stability and obeys the aerodynamic rules.

The effects of the grid fin geometry configuration are given. In Fig.4 and Fig.5, lift characters of all models are almost superposition except GSMX model and GSMY model, while drag coefficient of different model has large differences. This means that the grid fin lift-drag ratio can be increased using the decrease of its drag force. The drag coefficients and lift coefficients of GSMX model and GMSY model reduced much simultaneously. By this, we can know that it is not a good idea to increase the spacing between web, as larger spacing reduces the grid fin lifting piston. The lift character of GSMD model changes little, but its drag character changes much, which show that the grid fin frame cross section has great effect on the lift-drag ratio.

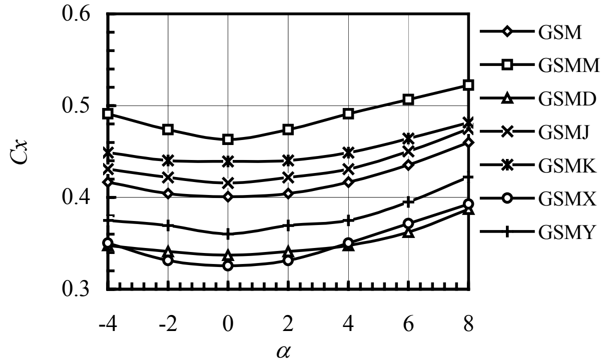

Fig.4 The drag coefficients at M_∞=2.5

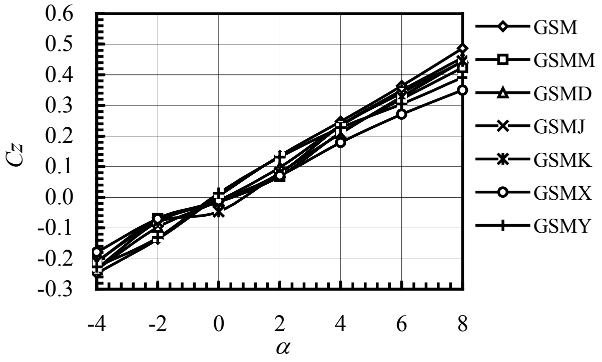

Fig.5 The lift coefficients at M_∞=2.5

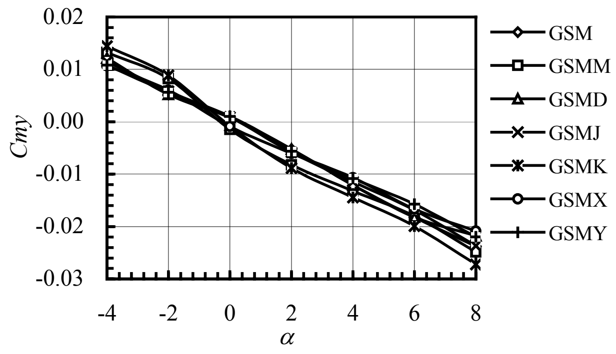

Fig.6 The pitching moment coefficients at M_∞=2.5

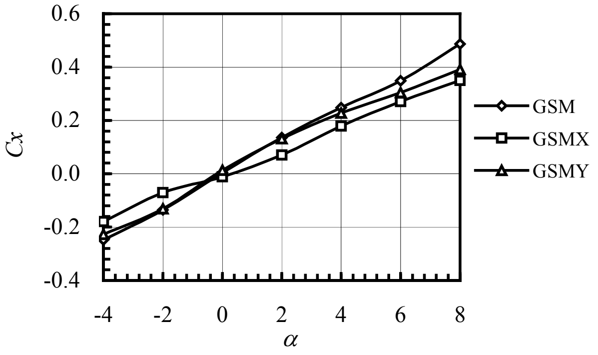

Fig.7 The lift coefficients of GSM, GSMX, and GSMY at M_∞=2.5

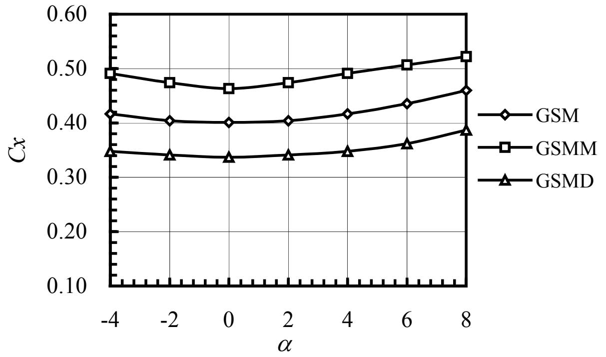

Fig.8 The drag coefficients of GSM, GSMM, and GSMD at M_∞=2.5

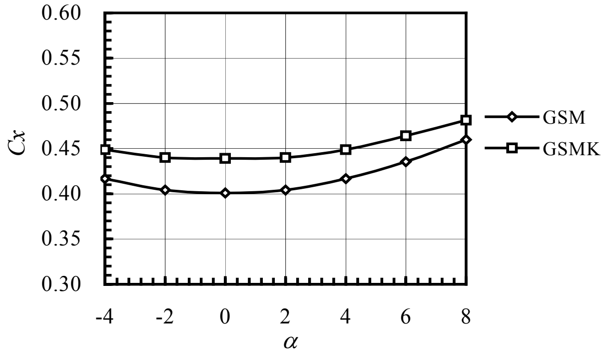

Fig.9 The drag coefficients of GSM and GSMK at M_∞=2.5

The effects of grid fin frame cross section on the drag coefficients are given below. Comparing the GSM model, SMD model, and GSMM model, their size and thickness of frame are the same, but their shapes of frame cross section are different. In Fig.5, we can know that the drag coefficients of GSMD model are the least, that those of GSM model are larger, and that those of GSMM model are the largest. The drag coefficients of GSMD model are less than those of GSM model by 16 percent, and less than those of GSMM model by 28 percent. It is obvious that the shape of frame cross section has great effect on its drag force. The shock wave character is affected by the shape of frame cross section at supersonic speeds. For GSMD model, its shock wave is the weakest, because whose frame windward plane is thin.

Therefore, the intension of its shock wave is weak, and its shock resistance is little. For GSMM model, its shock wave is normal shock wave, because its frame in windward plane is blunt. Therefore, the intensity of its shock wave is strong, and its shock resistance is large. While for the GSM model, the intensity of its frame shock wave and its drag coefficients are between those of GSMD model and GSMM model.

The effects of frame thickness on the grid fin drag coefficients are given below. In GSM model and GSMK model, the web cross section thickness and the frame cross section shape are both the same, only the thickness of GSMK frame is 0.2 mm thicker than that of GSM frame. We can calculate that the drag coefficients of GSMK model are larger than those of GSM model by 8 percent from Fig.9. This means that the thickness of frame has much greater effect on the grid fin.

Comparison with experimental results

GSM model simulation results were compared with the experimental results of wind tunnel tests (Chen *et al*., 1999) of GSZZ model at Mach 2.5 and at zero angle of attack. The geometry configurations of the two models were same, except for the blunt web of the experimental model and the tine web of the simulation model. Table 2 and Table 3 present the experimental results and computational results on drag coefficients, lift coefficients, and pitching coefficients respectively. Good agreement was found between the computed and experimental results in Table 2 and Table 3.

Table 2 Results of wind tunnel tests GSZZ model at Mach 2.5 and at zero angle of attack

GSZZ	α						
	−4°	−2°	0°	2°	4°	6°	8°
Cx	0.40374	0.39814	0.39558	0.39802	0.40481	0.41911	0.43986
Cz	−0.23169	−0.12161	−0.00427	0.11627	0.22987	0.34007	0.45527
Cmy	0.01423	0.00870	0.00217	−0.00494	−0.01092	−0.01638	−0.02262

Table 3 Computational results of GSM model at Mach 2.5 and at zero angle of attack

GSM	α						
	−4°	−2°	0°	2°	4°	6°	8°
Cx	0.41679	0.40422	0.40088	0.40422	0.41679	0.43546	0.45986
Cz	−0.24789	−0.13569	0.00392	0.13569	0.24789	0.36376	0.48654
Cmy	0.01212	0.00523	0.00103	−0.00523	−0.01212	−0.01821	−0.02375

CONCLUSION

We consider air as absolute gas, and disregard viscidity and boundary separation. Our numerical simulation of the grid fin aerodynamic character led to our conclusion given below:

The grid fin drag force is bigger than that of conventional planar fins, and the denser the grid is, the bigger is the drag force.

The grid fin frame has the greatest effect on the drag force, and the frame cross section shape has larger effect than the frame cross section thickness.

Compared with the frame, the thickness of the web cross section has little effect on the grid fin drag force. So, we can increase the thickness of web cross section to guarantee the intensity of grid fin.

It is not a good idea to reduce the number of web cross grids to decrease the grid fin drag force, because decreasing the number of web cross grids decreases the efficiency of the lift plane at the same time. This paper can serve as reference and guide for future design and research.

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