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Aerodynamics Simulation of Hypersonic Waverider Vehicle

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Abstract

The purpose of this paper is to examine the aerodynamic characteristics of three hypersonic configurations. Three hypersonic forebodies were designed. For the purpose to integrate with ramjet or scramjet, all forebodies were designed integrated with hypersonic inlet.

To better understand the forebody performance, three dimensional flow field calculations of these hypersonic forebodies integrated with hypersonic inlet were conducted in the design and off design conditions. Computational result show that waverider offer an aerodynamic performance advantage in the terms of high lift-drag ratios over the other two configurations. Liftbody offer good aerodynamic performance in subsonic region. The aerodynamic performance of the liftbody integrated with waverider configuration is not comparable to that of pure waverider in the terms of lift-drag ratios and is not comparable to that of pure liftbody in subsonic. But the liftbody integrated with waverider configuration exhibit good lateral-directional and longitudinal-directional stability characteristics. Both pure waverider and liftbody integrated with waverider configuration can provide relatively uniform flow for the inlet and offer good aerodynamic characteristics in the terms of recovery coefficient of total pressure and uniformity coefficient.

Keywords: Waverider, Liftbody, Inlet, Hypersonic, Forebody

1. Introduction

Hypersonic waveriders are promising shapes for the forebodies of propulsion-integrated hypersonic vehicles. The aerodynamic advantage of the waverider is that high pressure behind the shock wave under the vehicle does not "leak" around the leading edge to the top surface, so that the lift-to-drag ratio (L/D) for the waverider is considerably higher than that for the conventional aerodynamic vehicle. Furthermore, because they are designed with an inverse methodology, the flow field is first selected, then the appropriate generating shape is determined, the resulting shapes provide relatively uniform inlet conditions, corresponding to the flow conditions of the original generating flow(Charles E.Cockrell.J NASA-Technical-Paper-1996-3559).

Liftbody configuration is a promising shape for aero plane. It can offer good aerodynamic performance in subsonic region (Liu Wei(AIAA-2005-5250) .

The purpose of current research work is to integrate waverider with liftbody and examine the aerodynamic characteristics of three hypersonic configurations including pure liftbody configuration, pure waverider configuration and liftbody integrated with waverider configuration.

2. Hypersonic forebody and inlet design

In the derivation of forebody, the first step is to select design Mach number and then select the forebody shock wave's number and angle according to the inlet requirement(Xiao.Hong AIAA-2006-8090).

In this paper, we defined the design Mach number as 6.0, and the first shock wave angle was defined as 13.0(β_1).

According to equation of flow past the shock wave,

$$Ma_1^2 = \frac{Ma^2 + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1} Ma^2 \cdot \sin^2 \beta - 1} + \frac{\frac{2}{\gamma - 1} Ma^2 \cos^2 \beta}{Ma^2 \cdot \sin^2 \beta + \frac{2}{\gamma - 1}}$$

The Ma_1, which is Mach number after the first shock wave, can be calculated. According to Ma_1 and the second shock wave angle β_2, the Mach number Ma_2 after the second shock wave can be calculated.

The angle of shock wave can be defined by equal shock wave strength method, as

$$Ma\sin\beta_1 = Ma_1\sin\beta_2 = Ma_2\sin\beta_3$$

The angle of shock wave can also be defined by equal shock wave angle method, as

$$\beta_1 = \beta_2 = \beta_3$$

In this paper, we used equal shock wave angle method.

According to the Mach number before shock wave and angle, equation of angle of shock wave (β) and angle of flow swerve (α),the three angle of flow swerve $\alpha_1, \alpha_2, \alpha_3$ can be calculated.

$$\tan\alpha = \frac{Ma^2\sin^2\beta - 1}{\left[Ma^2\left(\frac{\gamma+1}{2} - \sin^2\beta\right) + 1\right]\cdot\tan\beta}$$

β_4 can also be calculated by flow swerve angle $\alpha_4 = \alpha_1 + \alpha_2 + \alpha_3$.

The forebody and inlet parameters are showed in Fig.1.

3. Pure waverider design

The design objective of waverider is that all three shock waves are closed in the design flight condition. As showed in Fig 2, in the design condition , the shock wave created by O_1 communicate to B, and the shock waves created by O_2,O_3 also communicate to B(O_1,O_2,O_3 are located in the same longitudinal profile).

Waverider design steps are described in the flowing:

(1) Select one point O at the top inlet curve willfully, and then find O_3 along negative X axial. The angle of O_3Oand X axial is $\alpha_1 + \alpha_2 + \alpha_3$ and the angle of O_3B and X axial is $\beta_3 + \alpha_1 + \alpha_2$.

(2) O_3 as the start point, then find O_2 along negative X axial. The angle of O_2O_3 and X axial is $\alpha_1 + \alpha_2$ and the angle of O_2B and X axial is $\beta_2 + \alpha_1$.

(3) O_2 as the start point, then find O_1 along negative X axial. The angle of O_1O_2 and X axial is α_1 and the angle of O_1B and X axial is β_1.

(4) Repeat the step (1) (2) (3) along the top inlet curve. Join all the O_1, and then get the first leading edge. Join all the O_2, and then get the second leading edge. Join all the O_3, and then get the third leading edge.

(5) Form the first compress surface by the first leading edge and the second leading edge. Form the second compress surface by the second leading edge and the third leading edge. Form the third compress surface by the third leading edge and the top inlet curve. All three compress surfaces form the waverider bottom compress surface.

(6) Move the first leading edge along flow direction (X axial) to get the top surface of waverider.

We define the design Mach number $Ma = 6.0$ and the angle of shock wave $\beta_1 = \beta_2 = \beta_3 = 13^0$. The inlet height is 30mm and inlet width is 150mm.

4. Liftbody design

The liftbody design steps(Saltzman and Edwin J AIAA-1999-0383) are described in the flowing:

(1) Define top view curve of liftbody.

(2) Define top surface curve.

(3) Define compress surface.

(4) Define forebody bottom surface.

5. Liftbody integrated with waverider configuration design

In this configuration design, the bottom surface is same to the waverider design steps and the top surface is same to liftbody design steps(Zhenxia Liu and Xiao Hong AIAA-2007-5413) .

Three hypersonic inlets are designed by same parameters.

Three hypersonic models are given in Fig.5-7.

6. Simulation

To better understand the forebody performance, three dimensional flow field calculations of these hypersonic forebodies integrated with hypersonic inlet were conducted in the design and off design conditions.

We have used our developed-in-home CFD code to simulate the flow around the forebody with the flow in the inlet. We used the Roe's flux differencing scheme with the min -mod flux limiter to achieve second-order spatial accuracy. This Navier–Stokes code uses Sutherland's viscosity model and the ideal gas law to compute the gas density. The ratio of the specific heats was assumed to be 1.4. We used 1132300 grid cells in the computation. Aerodynamic characteristics of each of configurations are examined over the Mach number range from 0.5 to 8.0 and the attack angle range from -6 to 10, and the performance of these configurations are compared to that of the pure waverider configuration. Effects of attach angle on aerodynamic performance of hypersonic configuration at Ma=6.0 are shown in Fig.8. The maximum lift-drag ratio for each configuration also occurs near 2 angle of attack at Mach 6.0. The angle of attack for maximum lift-drag ratio increases as Mach number decreases. A direct comparison of three configurations is shown in Fig.8. The pure waverider configuration produces higher values of lift-drag ratio than the other two configurations at each Mach number.

The pitching-moment characteristics of three configurations are shown in figure 9. This figure shows the pitching-moment coefficient versus angle of attack at each Mach number 6.0. The moment reference center location here is an arbitrarily selected location at the approximate location of the center of gravity of the model. The liftbody integrated with waverider configuration was expected to provide improved directional stability.

To compare the performance of the waverider in this paper with the two others, We define the performance parameter as flowing:

(1) Flow coefficient

$$\alpha = \frac{A_\infty}{A_1} = \frac{\rho u}{(\rho u)_\infty}$$

A_∞ The free flow tube area A_1 The inlet area

(2) Recovery coefficient of total pressure

$$\eta = \frac{P_2}{P_0}$$

P_2 Average total pressure in the inlet exit profile P_0 Total pressure of free flow

(3) Uniformity coefficient

$$\varepsilon = \frac{\sum_{I=1}^{N} \sqrt{(M_I - \overline{M})^2}}{N \times \overline{M}}$$

$\overline{M}$ Average Mach number in the inlet out profile

M_I Mach number in the I node

N Node number

Compared with two comparative reference models, the liftbody integrated waverider configuration show better performance with the flow coefficient increased by 5.96%, 14.8%; the recovery coefficient of total pressure increased by 5%, 10.5%, respectively; the uniformity coefficient of inlet outlet is increased by 2.1%, 6.3%.

7. Conclusion

The purpose of this paper is to examine the aerodynamic characteristics of three hypersonic configuration ns including pure liftbody configuration, pure waverider configuration and liftbody integrated with waverider configuration.

Hypersonic forbodies were designed based on these configurations. For the purpose to integrate with ramjet or scramjet, all the forebodies were designed integrated with hypersonic inlet.

To better understand the forebody performance, three dimensional flow field calculations of these hypersonic forebodies integrated with hypersonic inlet were conducted in the design and off design conditions. Computational results show that waverider offers an aerodynamic performance advantage in the terms of higher lift-drag ratios over the other two configuration ns. Liftbody offer good aerodynamic performance in subsonic region. The aerodynamic performance of the liftbody integrated with waverider configuration is not comparable to that of pure waverider in the terms of lift-drag ratios and is not comparable to that of pure lift body in subsonic. But the liftbody integrated with waverider configuration exhibit good lateral-directional and longitudinal-directional stability characteristics. Both pure waverider and liftbody integrated with wave rider configuration can provide relatively uniform flow for the inlet and offer good aerodynamic characteristics in the terms of recovery coefficient of total pressure and uniformity coefficient.

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Saltzman, Edwin J ect. (1999). Flight-determined subsonic lift and drag characteristics of seven Lifting-body and wing-body reentry vehicle configurations with truncated bases.AIAA-1999-0383.

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Table 1. Performance comparison of forebody integrated with inlet

Model	Pure Waverider	Liftbody	Liftbody integrated with waverider
Mass flow rate	3.02	2.786	3.2
Total pressure recovery coefficient	0.40	0.38	0.42
Average Mach in the inlet exit profile	2.0	2.3	2.05
Uniformity coefficient	0.193	0.201	0.189

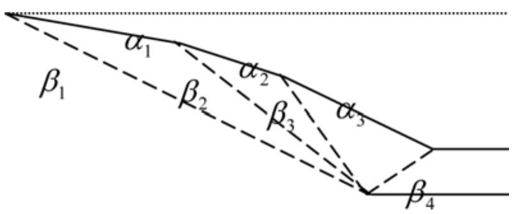

Figure 1. Forebody and inlet parameters

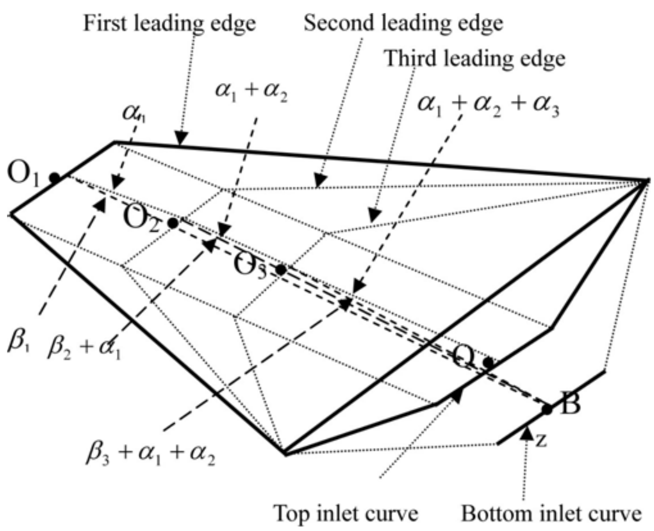

Figure 2. Pure waverider design

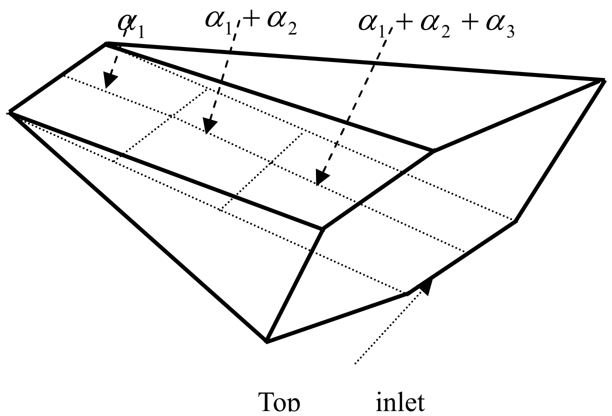

Figure 3. Liftbody Design

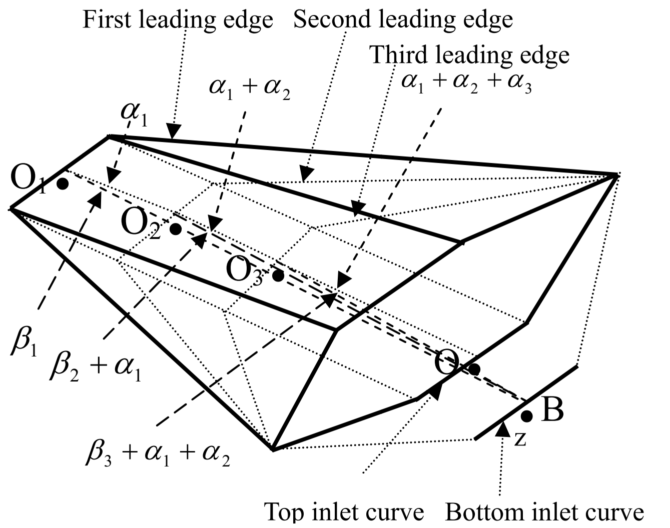

Figure 4. Liftbody integrated with waverider configuration design

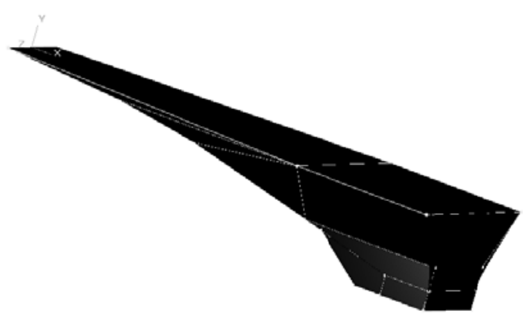

Figure 5. Pure Waverider Model

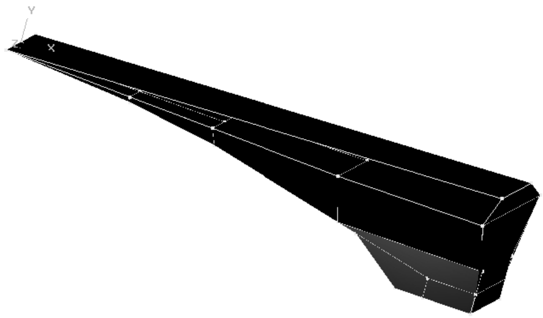

Figure 6. Liftbody Model

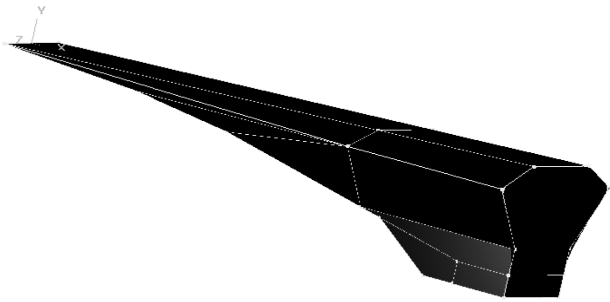

Figure 7. Liftbody Integrated with Waverider Model

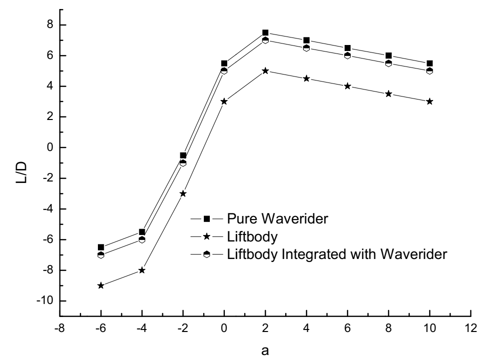

Figure 8. Effects of attack angle on aerodynamic performance of hypersonic configuration at Ma=6.0

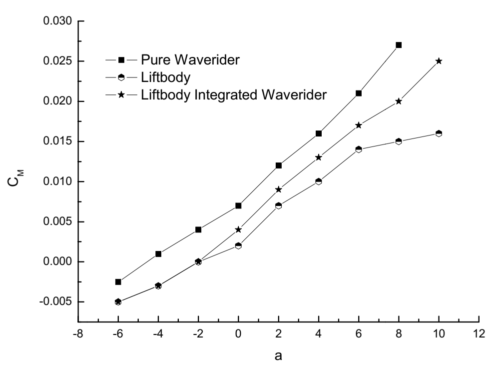

Figure 9. Effects of attach angle on Cm of hypersonic configurations at Ma=6.0