Optimization Design of High Lift to Drag Ratio Waverider Vehicle Based on Viscosity Simulation

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Abstract. Based on the shock-fitting method, the optimization design of waverider is studied by introducing the influence of height. The numerical simulation results show that the blunted leading edge and the upper surface modification do not increase too much resistance, the viscous lift-to-drag ratio is still greater than 4.0, which opens a new way for the practical application of waverider vehicle.

Introduction

The waverider concept was first introduced by Nonweiler in 1958, which is a sort of configuration derived from a known, analytic flow field, such as flow over a two-dimensional wedge or flow around a slender cone, as shown in Figure 1. Waverider is considered as an effective way to break through the lift-to-drag barrier. However, waverider configuration cannot be directly used for hypersonic vehicle because of the aerodynamic heating problem on its sharp leading edges. However, most of the studies focus on the method of generating waverider, which aims to improve the flexibility and theoretical performance of waverider design [1-3]. Takashima’s study shows that the bluntness of the leading edges is considered to be the primary reason for decreases in aerodynamic performance for the waverider [4]. Gillum’s wind tunnel test shows that considering the bluntness the ratio of lift to drag decreases from 4.61 to 3.7 compared with the theoretical model [5].

The above research has not considered the loss of the lift-to-drag ratio performance when the volume has to increase. The theoretical waverider still has a large distance from hypersonic vehicle, so it is necessary to carry out in-depth research on the practical design of waverider. In this paper, the practical waverider design method is studied to increase the interior filling space and reduce the heat flux, which is under the premise of ensuring the characteristics of high lift-to-drag ratio.

Optimization Parameters

In general optimization design of waverider, Mach number, semi-conical angle $\delta$ and baseline $z=f(x)$ are usually taken into account. Considering the actual flight mission, the parameter of altitude $H$ must be introduced into the optimization, which is due to the fact that the theoretical waverider is based on the inviscid flow field, and the ratio of lift to drag does not take into account the influence of viscous
force. At a given Mach number, with the height increasing, the Reynold number decreases, the thickness of boundary layer increases, the ratio of viscous force increases, and the ratio of lift to drag decreases significantly. At 40km altitude, the friction resistance and shape resistance of waverider vehicle are the same. But at 70 km, friction will account for about 70% of the total resistance. At this time, the increase of lift will also lead to the increase of friction resistance. Therefore, no matter how the shape is optimized, the ratio of lift to drag will not increase significantly. At the same time, with the increase of the height, the thin air eases the aerodynamic heating, so the leading edge radius can be further reduced, which is favorable to the front shock wave appendage and increases the lift-to-drag ratio.

In conclusion, in order to obtain a waverider vehicle with high lift-to-drag ratio, the design process should be based on the scale of vehicle and the actual mission requirements, select the appropriate flight altitude and Mach number as the design point of waverider, which makes the vehicle meet the design requirements of both aerodynamic and thermal aspects. Finally, the height of friction equal to shape resistance(40km) is chosen as the design point of waverider vehicle, which maximizes optimization space of aerodynamic configuration.

**Optimization Design of Waverider Vehicle**

**Shock-Fitting Method**

In this paper, the waverider design method based shock-fitting method[6] is applied to get the theoretical shape and then the practical design is carried out according to the actual loading requirements and thermal environment constraints. Analysis results shows that the waverider designed from a certain type of shock generating shape has a better aerodynamic performance in terms of lift-to-drag ratio and longitudinal stability, which indicates that the proposed waverider design methodology is a promising approach for designing waverider vehicles with better aerodynamic performances comparing to traditional waverider design method.

![Shock-fitting method](image)

Figure 2. Comparison between shock-capturing method and shock-fitting method.

**Leading Edge Bluntness**

The leading edge of the theoretical waverider is preserved, and on the basis of it, the given radius is taken to generate the blunt leading edge. The design of the leading edge bluntness of the waverider can ensure that the shape of the upwind surface of the waverider remains the same and minimize the influence on the characteristics of the upwind flow field as much as possible, as shown in Figure 3.
In this paper, the influence of different bluntness radius on the aerodynamic characteristics of waverider is compared. Numerical simulation results based on solving laminar N-S equations are shown in Table 1. Inflow conditions are Ma=12, H= 40 km. The waverider decreases with the increase of bluntness radius, when the bluntness radius exceeds 1% of the characteristic length. The lift-to-drag ratio of the waverider is similar to that of the lifting body or wing-body, and no longer has the advantage of high lift-to-drag ratio. The surface pressure distribution and the surface limit streamline under the waverider is shown as Figure 4. When the bluntness radius is less than 1% of the character length, the distribution of air flow through the leading edge is uniform, which accords with the characteristics of streamline tracing, and the high pressure airflow is compressed on the lower surface, resulting in high lift-to-drag ratio. When the bluntness radius is more than 1%, the ratio of lift to drag decreases significantly. Because the front shock wave cannot be attached to leading edge, the lower surface high pressure air flows around the upper surface of the leading edge flow.

In order to take into account the high lift-drag ratio and the lower aerodynamic heating, the characteristic length of 0.25% is chosen as the bluntness radius. Compared with the theoretical shape, the maximum lift-to-drag ratio decreases within 5% and still reaches 4.9.

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Table 1. Lift-to-drag ratio with different leading bluntness radius.

Optimized Loading Volume

In order to increase the effective volume of the waverider shape, the leeward surface shape of the waverider can be adaptively modified according to the actual demand on the premise of keeping the same upwind surface shape of the waverider. Thus, the freestream flow characteristics of the leeward surface are no longer guaranteed. However, the influence on the characteristics of the upwind surface is relatively small. The specific design idea of this paper is: Raise the center line in front of the leeward at a certain angle to increase the available space of the structure. The latter half is parallel to the freestream flow and further reduces the leeward surface resistance, as shown in Figure 5.
elevation angle of the upper surface is consistent with the angle of attack, and the air resistance is minimized during cruising.

![Image](image1.png)

Figure 5. Optimal design of filling space.

The influence of filling space optimization on the theoretical waverider characteristics is evaluated. It can be seen from Figure 6, that the maximum lift-to-drag ratio decreases by about 20% after the surface modification on the waverider, but the filling space is increased nearly 1 fold; Meanwhile, from the flow field pressure cloud chart, the optimized shape still has the character of waverider, as shown in Figure 7.

![Image](image2.png)

Figure 6. Lift-to-drag ratio characteristics.  
Figure 7. Pressure cloud of flow field.

**Conclusions**

Based on the theoretical method of generating waverider and by introducing the influence of height, the practical shape of waverider is designed, and the aerodynamic and thermal characteristics are studied by numerical simulation. The results show that:

When the height of waverider design point is more than 40 km, the lifting effect brought by shape optimization will be less than that of friction increase, and the lift-to-drag ratio of vehicle will not be further improved.

When the bluntness radius is larger than 1% of the characteristic length, the lower surface flow characteristics of the waverider will change significantly, and the shock wave will no longer attach to the leading edge and the transverse flow will occur. The lift-to-drag ratio decreased significantly;

When the upper surface of the theoretical waverider is locally raised, the leading edge is blunted and the aerodynamic control surface is assembled, the viscous trimmed lift-to-drag ratio of the vehicle which is designed by shock-fitting method is still greater than 4.0. It is proved that the practical design of the waverider is an important development direction of hypersonic vehicle in the future.

**References**


