Design and computational study of practical waverider configuration with high performance

Jianhui Wu¹, Yue Zhao, Pengju Hu and Jieqi Li
China Academy of Launch Vehicle Technology R&D Center
¹Email: 13488789407@163.com

Abstract. Based on the theoretical method of generating waverider bodies, the practical waverider is designed by introducing the influence of height, and the aerodynamic and thermal characteristics are studied by numerical simulation. The results show that the blunted leading edge and the upper surface modification do not increase too much resistance, the viscous trimmed lift-to-drag ratio is still greater than 4.0, and the vehicle has the dynamic stability in yaw and roll direction, which opens a new way for the practical application of waverider vehicle.

1. Introduction
Waverider is considered as an effective way to break through the lift-to-drag barrier. Because of its advantages such as easy to reverse design and good performance of non-design points, it has been widely studied by many scholars since it was proposed by Nonweiler. 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 aerodynamic control rudder is assembled and 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.

2. Design of waverider vehicle

2.1. Design points for waverider
Taking the design method of cone-guided waverider as an example, the shape of theoretical waverider is determined by the following parameters: freestream flow Mach number, semi-conical angle δ, baseline z=f(x), as shown in figure 1. However, considering the actual flight mission, the design parameter of altitude H must be introduced in the design of waverider vehicle, 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 Reynolds 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.

**Figure 1.** Design method of cone-guided waverider.

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.

2.2. Practical design of waverider vehicle

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.

2.2.1. 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 2.

2.2.2. 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 3. The elevation angle of the upper surface is consistent with the angle of attack, and the air resistance is minimized during cruising.
2.2.3. Aerodynamic control surface design. In order to improve the stability and the maneuverability of the vehicle, the practical design of the waverider is continued. Compared with the single vertical tail, the V-tail is more efficient in the forward angle of attack, although the resistance is increased. The V tail can participate in pitch and yaw control and the elevator can take part in pitching and rolling control as shown in the figure 4.

3. Numerical simulation method
In this paper, the aerodynamic characteristics of the waverider are calculated by solving perfect gas N-S equation. The second-order upwind TVD scheme is used in spatial discretization [7]. The time discretization is based on the implicit LU-SGS scheme. Because the height of the design point of the waverider vehicle is 40km, the aerodynamic flow is chosen as laminar flow, and the aerodynamic heat calculation takes the transition effect into account and uses the full turbulence calculation. SST model is chosen for turbulence model.

The structure grid is used to divide the waverider vehicle, as shown in the figure 5. The traditional hypersonic vehicle has very small bottom resistance, so the bottom flow is often not considered in aerodynamic evaluation. However, the drag of the waverider vehicle itself is very small, so the bottom grid is also divided. Considering that the calculation of heat flux is very sensitive to the grid distribution. The thickness of the reference boundary layer is about one order of magnitude smaller than that of the first layer.

4. Calculation and analysis
4.1. Validation of practical design method for waverider
In this paper, the influence of different bluntness radius on the aerodynamic characteristics of waverider is compared. It can be seen from the figure 6. that 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 7. 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.

![Figure 6. Lift-to-drag ratio vs. radius of leading edge.](image)

![Figure 7. Surface streamline and pressure cloud diagram of different leading bluntness radius (left: radius less than 1%; right: radius greater than 1%).](image)

Secondly, the influence of filling space optimization on the theoretical waverider characteristics is evaluated. It can be seen from figure 8. 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 9.
4.2. Analysis of aerodynamic characteristics

4.2.1. Trimmed lift-to-drag ratio. The calculation results of the trimmed lift-to-drag ratio of the waverider vehicle are shown as figure 10. The Mach number ranges from 3 to 18, the corresponding flight altitude is from 5 km to 65 km, and the maximum lift-to-drag ratio is 4.15, which appears at Ma8, angle of attack 4 °.

4.2.2. Flight stability and maneuverability. The curves of longitudinal pressure center with Mach number in rudderless vehicle are shown in figure 11. The variation range of longitudinal pressure center with Mach number at the same angle of attack is less than 0.5%. The curve of pitch moment coefficient of waverider vehicle varies with the rudder angle as shown in figure 12. The range of rudder deviation is -13.1 ° and 4.9 °. It is proved that the body and the control rudder surface are designed with both flight stability and maneuverability.

The curves of roll moment coefficient and lateral pressure center change with attack angle are shown in the figure 13 and 14. It can be seen that Cmx β is less than 0 in all calculated states, and the rolling direction is static stable. The lateral center Xcpy is greater than 0.65, and the static stability margin is greater than 4% when the yaw direction is statically stabilized at 4 °angle of attack.

The curves of CMy β dyn change with attack angle at different Mach numbers are shown in figure 15. It can be seen from the figure that CMy βdyn are less than 0 in the calculated state. The yaw direction is dynamically stable. The curve of LCDP changes with angle of attack at different Mach numbers is shown in figure 16. From the figure, LCDP is less than 0 in the calculated state. Aileron reversal will not occur. It is proved that the vehicle has good stability in both yaw and roll direction.
Figure 1. Longitudinal pressure center vs. Mach number.

Figure 2. Pitch moment vs. rudder angle.

Figure 3. Rolling moment vs. attack angle.

Figure 4. Lateral pressure center vs. attack angle.

Figure 5. CMy β, dyn vs. attack angle.

Figure 6. LCDP vs. attack angle.

4.3. Analysis of aerothermodynamic characteristics

Figure 17 shows the distribution of heat flow in the leading edge of the waverider vehicle. The maximum cold wall heat flux can be seen at the stationary point, reaching 7 MW/m$^2$. At the same time,
the heat flux of the lower part of the whole leading edge is obviously higher than that of the upper part because of the attached shock wave, and the mean value of the heat flux of the lower part is more than 1.5 MW/m². The heat flux of the central line of the leeward surface decreases rapidly with the increase of the axial distance. When the characteristic length is greater than 10%, the heat flux is about two orders of magnitude lower than that of the stationary point, as shown in figure 18.

Figure 17. Heat flux distribution on leading edge.

Figure 18. Dimensionless heat flux of the center line of the symmetrical plane of the waverider vehicle.

5. 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
[1] Mark J L 2005 Shock-based waverider design with pressure gradient corrections and computational simulations Journal of aircraft 42(5)
[2] Pan J and Yan C 2008 Aerodynamic study of three waveriders based on a new optimization process AIAA paper 170
[3] Konstantinos K 2017 Efficient parameterization of waverider geometries Journal of aircraft 54(3)
[4] Takashima N and Mark J L 1994 Navier-Stokes computation of a viscous optimized waverider. Journal of Spacecraft and Rockets 31(3) 383-391
[5] Michael J G and Mark J L 1997 Experimental results on a mach 14 waverider with blunt leading edges Journal of aircraft 34(3)
[6] Chen B Y, Liu C Z and Ji C Q 2017 Waverider design and anslysis based on shock-fitting method ACTA Aerodynamica sinica 35(3) 421-428
[7] Xie J R and Wu S P 2007 TVD scheme and numerical simulation of aerodynamic heating in hypersonic flows Journal of Beijing University of Aeronautics and Astronautics 33(4)