# Numerical study on aerodynamic performance of waverider with a new bluntness method

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**SAGE** 

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#### Abastrct

The waverider is deemed the most promising configuration for hypersonic vehicle with its high lift-to-drag ratio at design conditions. However, considering the serious aero-heating protection, the sharp leading edge must be blunted. The existing traditional bluntness methods including the following two types: "reducing material method" and "adding material method". Compared to the initial waverider, the volume will be smaller or larger using the traditional methods. With the fixed blunted radius, the volume and aerodynamic performance is determined. In this paper, a new bluntness method which is named "mixing material method" is developed. In this new method, a new parameter is introduced based on the traditional two bluntness methods. Under fixed blunted radius, the volume and aerodynamic performance can be changed within a wide range by adjusting the parameter. When the parameter is 0 and 1, the novel blunted method degenerated into the "reducing material method" and "adding material method" respectively. The influence of new parameter on the aerodynamic characteristics and volume are studied by numerical simulation. Results show that the volume, lift and lift-to-drag ratio increases with the increase of the parameter under the fixed blunt radius, but simultaneously, the drag will also increase. Therefore, considering the different requirements of the air-breathing hypersonic aircrafts for the balance of thrust and drag, lift and weight, a suitable bluntness parameter can be selected to achieve a balance. This research can provide reference for hypersonic waverider vehicle design.

#### **Keywords**

Waverider, bluntness method, hypersonic, volume, computational fluid dynamics

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### Introduction

The waverider configuration is widely used in hypersonic vehicles with its good lift-to-drag ratio aerody-namic performance.<sup>1–10</sup> The waverider was first proposed by Nonweiler<sup>11</sup> in the 1950s. According to the given flow field, the configuration is designed by means of shock surface cutting and streamline tracing. Under the designed flight conditions (given Mach number, angle of attack, etc.), the bow shock generated in high-speed flight is completely attached to the outer edge of the aircraft, the upper and lower surfaces of the aircraft have no flow leakage, and the highpressure area after the shock wave is completely wrapped in the lower part of the aircraft, so that the aircraft can obtain a high lift-to-drag ratio. It is called "waverider" because it seems to ride on the shock wave. In recent years, with the development of air-breathing hypersonic vehicle research, this concept has attracted more and more attention, and it has gradually become practical. For example, the

precursor of X-51A<sup>12</sup> aircraft in the United States is designed by waverider.

The design method and performance evaluation of waverider is one of the important research directions. Huang Wei et al.<sup>13</sup> studied the influence of different parameters (inflow Mach number, angle of attack and sideslip angle) on the aerodynamic performance of hypersonic waverider vehicle. Ding Feng published

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several papers<sup>8,14–18</sup> on the design method and fullscale waverider design, which provides an important reference for the design and application of waverider. Cui Kai et al.<sup>19-21</sup> used a new method to derived the waverider configuration from the general conical flow field. In addition, the waverider configuration is applied to the design of high pressure capture wing, which can effectively improve the aerodynamic performance of the waverider aircraft. Li Shibin et al.<sup>22,23</sup> proposed a new type of aircraft which is applied to the high-speed waverider configuration in a wide speed range, and studied the influence of the connection part on the aerodynamic performance of the new waverider configuration. Rasmussen et al.<sup>24–26</sup> obtained the waverider configuration by using the hypersonic small disturbance theory and numerical simulation technology. B. Mangin et al.<sup>27</sup> used a new method to obtain the waverider configuration from the conical body and the axisymmetric power-law blunt body. Compared with the waverider derived from conical body, the lift-to-drag ratio of the waverider body obtained by optimizing the powerlaw blunt body is similar, but the volume increases by about 20%.

The waverider consists of upper surface, lower surface and back surface.<sup>28</sup> The upper surface is generally the inflow surface, and the lower surface is the compression surface which provides the lift. According to the design principle, the leading edge of the waverider needs to be infinitely sharp. However, restricted by aerodynamic heating, sharp leading edge needs to be blunted. Many scholars have studied the bluntness impact on the aerodynamic performance of waverider. Takashima et al.<sup>29</sup> used the cross section cutting method to blunt the leading edge of the waverider. Tincher et al.<sup>30</sup> raised the upper surface of the waverider and make the circumscribed circle of the lower compression surface, so as to ensure the aerodynamic performance of the lower surface. The influence of bluntness on the aerodynamic performance of waverider was studied by experi-ment in literature.<sup>31,32</sup> In addition, the influence of power curve bluntness<sup>33</sup> and artificial blunt leading edge<sup>34</sup> on the aerodynamic performance of the blunt waverider is also studied; the aerodynamic performance of the blunt waverider in the rarefied gas<sup>35</sup> is analyzed.

In this paper, a lot of research work on waverider is reviewed, which makes a great contribution to the design and research of hypersonic waverider. But we also find that the traditional bluntness methods have certain limitations. When the blunted radius is given, the volume and aerodynamic performance is determined. A new bluntness method is developed by introducing a new parameter in this paper, and the influence of bluntness parameter on the aerodynamic performance of waverider is analyzed. The following work of this article is as follows: the next section introduces the bluntness method and numerical method; the Aerodynamic performance of base waverider section presents the results of waverider with sharp leading edge; the Results and discussion section discusses the numerical results of waverider with different bluntness parameter; the last section concludes with the work.

#### **Bluntness methods**

Although the details of the aforementioned bluntness methods are slightly different, the traditional bluntness methods can be basically classified into two categories: "adding material method" and "reducing material method". This part mainly introduces three bluntness methods: two traditional bluntness methods and a new bluntness method. The bluntness of the waverider is mainly related to the upper and lower surfaces. For the convenience of analysis, the upper and lower surfaces of the waverider are simplified into two profile lines. Simplified profile lines are shown in Figure 1(a). The horizontal line represents the upper surface, the other line represents the lower surface. The intersection point of two lines represents the curve in three-dimension waverider.

"Reducing material method"<sup>29</sup> is shown in Figure 1(b), where r is the blunt radius. The detail of bluntness method is as follows: the upper and lower surfaces of the waverider keep unchanged, and the leading edge was directly cutted off by blunt radius. The volume of blunt waverider model is smaller than the initial waverider, so this method is



**Figure 1.** Bluntness methods and configuration of waverider (a) simplified profile lines (b) "reducing material method"<sup>29</sup> (c) "adding material method"<sup>30</sup> (d) "mixing material method" (e) bluntness waverider model.

called "reducing material method". The volume of the waverider bluntness method decreases with the increasing of blunt radius.

"Adding material method"<sup>30</sup> is shown in Figure 1(c). The upper surface of the waverider was translated to a specific height (the height is the blunt diameter). The volume of blunt waverider model is larger than the initial waverider. Therefore, this method is called "adding material method" and the volume of the waverider bluntness method increases with the increasing of blunt radius.

"Mixing material method" is shown in Figure 1(d). The upper surface of the waverider was translated to a distance h, and h is equal to the coefficient  $\lambda$  multiplied by the blunt diameter (2r). The coefficient  $\lambda$  is in range 0 to 1, and different configurations can be obtained by given the different coefficient  $\lambda$ . When coefficient  $\lambda$  is 0 and 1, the "mixing bluntness method" degenerate into the "reducing material method" and "adding material method" respectively. The volume of the waverider obtained by this bluntness method both can be increased or decreased with respect to the initial waverider configuration, so it is called "mixing material method". The volume of waverider by this bluntness method can be changed flexibility with increasing of blunt radius.

The 3-dimensional bluntness waverider is shown in Figure 1(e). The initial waverider is generated based on an elliptical cone with an aspect ratio (width to length) of 0.618, the cone angle is  $7.09^{\circ}$  and the length of waverider is 2 meter. The blunt radius of waverider is 2 mm, 5 mm and 10 mm. Under the fixed blunt radius, the coefficient  $\lambda$  varies from 0 to 1 with an interval of 0.2. The layout of the numerical plan is shown in Table 1. In order to obtain the angle of attack with the maximum lift-to-drag ratio, the aerodynamic performance evaluation of the waverider at different angles of attack is conducted. Results show that the maximum lift-to-drag ratio with sharp leading edge occurs at 2° angle of attack. In order to compare with the maximum lift-to-drag ratio of the sharp leading edge of waverider, the aerodynamic performance evaluation of the different bluntness methods is conducted at  $2^{\circ}$  angle of attack.

# Aerodynamic performance of base waverider

This part mainly studies the aerodynamic performance of the sharp leading edge of waverider.

Calculation conditions: the incoming flow is Mach number 6, the flight altitude is 25km, and the wall adopts non-slip insulation wall. The turbulent k-& model is used. In order to improve the reliability of the numerical results, the grid convergence tests are carried out first. Due to the limitation of boundary layer and meshes number, it is necessary to investigate the aerodynamic performance of waverider with different near wall sizes and mesh numbers under the same topology, therefore four sets of grids with the same topology but different grid distribution parameters are used for the tests. In the test case, the leading edge of waverider is taken for analysis, and the calculation is carried out under the condition of 0° angle of attack. Since the waverider is symmetrical, half of waverider is used for calculation. The computational grid is shown in Figure 2. The results of grid convergence are shown in Table 2. L is the reference length of the waverider (2m). The X direction is the length direction, the Y direction is the width direction, and the Z direction is the height direction. The length of waverider is 2m, the maximum width of waverider is 0.74m, the maximum height of waverider is 0.18m. The length of far field is 2.93m, the maximum width of far field is 1.9m, the maximum height of far field is 3.17m.

It can be seen from Table 2 that the aerodynamic performance difference is about 4% with the increase of the near wall dimension and the increase of the



Figure 2. Waverider computational grid.

Table	١.	The	layout	of	the	numerical	plan.
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Туре	Angle of attack (degree)	Blunt radius (mm)	Coefficient $\lambda$
Sharp waverider	0,1,2,3,4,6,8,10	_	_
Bluntness waverider	2	2	0, 0.2, 0.4, 0.6, 0.8, 1
		5	0, 0.2 ,0.4 ,0.6 ,0.8, 1
		10	0, 0.2, 0.4, 0.6, 0.8, I

Number	Near wall size (mm)	Drag (N)	Lift (N)	L/D	Grid number
I	L*10 <sup>-4</sup>	499.61	2050.16	4.10	1857600
2	2.5L*10 <sup>-5</sup>	498.35	2003.09	4.01	1857600
3	L*10 <sup>-5</sup>	504.12	1997.85	3.96	1857600
4	L*10 <sup>-5</sup>	506.37	1992.99	3.94	3436788

Table 2. The calculation results of grid convergence.



Figure 3. The lift-to-drag ratio of the waverider with sharp leading edge.

material grid. It can be considered that the numerical methods are reliable. The following numerical results are calculated with the third set of grids.

In order to investigate the accuracy of the numerical methods employed in this study, hypersonic models<sup>36,37</sup> with wind tunnel test data need to be used to validate the reliability of the sover code. Our research team published an article on high pressure capture wing<sup>21</sup> in 2017, in which cones and HB-2 models were carried out to verify and validation work of the numerical calculation method. In this paper, the mesh scales and turbulence model are the same as those of cones and HB-2 models in literature,<sup>21</sup> so this part will not be repeated.

The lift-drag ratio of the waverider with sharp leading edge is shown in Figure 3. L/D is lift-todrag ratio. The lift-to-drag ratio increases with the increase of the angle of attack in the range of  $0^{\circ}-2^{\circ}$ , and it decreases with the increase of the angle of attack in the range of  $2^{\circ}-10^{\circ}$ . The maximum lift-todrag ratio occurs at  $2^{\circ}$  angle of attack and the maximum lift drag ratio is 5.19.

Pressure of lower surface along symmetry plane and bottom plane with sharp leading edge are shown in Figure 4 (a) and (b) respectively. The label represents angle of attack, x and y denote the coordinate, L and W denote length and width of waverider. The pressure distribution of different angles of attack on the same section is similar, but the pressure increases with the increase of the angle of attack. Pressure contours of waverider with sharp leading edge with  $2^{\circ}$  angle of attack are shown in Figure 5. Figure 5(a) is the pressure contour in the symmetrical plane and Figure 5(b) is the pressure contour in the bottom plane. The high-pressure area of the waverider is mainly on the lower surface, and there is almost no pressure leakage in lower plane. The pressure of flow field in the bottom plane is uniform.

## **Results and discussion**

In order to investigate the influence of different bluntness parameters on the aerodynamic performance of waverider, based on CFD numerical simulation, the comparative analysis of different bluntness methods on the drag, lift and lift-to-drag ratio of waverider was carried out. The angle of attack of the aerodynamic performance of the waverider with different bluntness methods is at  $2^{\circ}$  and other boundary conditions are the same as those of the sharp leading edge of waverider.

#### Characteristics of drag

Drag of waverider under different bluntness parameters is shown in Figure 6, where 0, 0.2...1 is the bluntness parameter.  $\lambda = 0$  indicates "reducing material method" and  $\lambda = 1$  indicates "adding material method", the others indicate "mixing material method". It can be seen from Figure 6 that under the fixed blunt radius, the drag increases with the increase of parameter. With the fix blunt radius from 2 mm to 10 mm, the increase amplitude of drag increases with the increases with the flow direction projection area. In addition, with the fixed coefficient, drag increases with the increases of blunt radius.

Pressure of blunted waverider along the center line is shown in Figure 7. Pressure is presented in terms of pressure coefficient  $C_p$  is normalized by  $\rho_{\infty}^2 v_{\infty}^2/2$ . It can be seen from Figure 7 that the pressure distribution trend of the waverider pressure along the centerline under different parameters is similar.

Pressure contours of blunt waverider in symmetrical plane are shown in Figure 8. Figure 8(a) is "reducing material method" ( $\lambda = 0$ ) pressure contour, Figure 8(b) is "adding material method" ( $\lambda = 1$ ) pressure contour. The pressure contour of the blunt waverider in the symmetrical plane is similar under different parameters, but the difference is the high-



Figure 4. Pressure of lower surface with sharp leading edge along the slices (a) Symmetry plane, (b) Bottom plane.



Figure 5. Pressure contours of waverider with sharp leading edge under 2° angle of attack (a) Symmetry plane, (b) Bottom plane.



**Figure 6.** Drag of waverider under different bluntness parameters.

pressure region of compression surface increases with the increase of the parameter.

Pressure contours in symmetric plane of waverider  $(\lambda = 1)$  with different blunt radius are shown in Figure 9. Figure 9(c) is pressure contour of 2 mm blunt radius of waverider, Figure 9(d) is pressure contour of 10mm blunt radius of waverider. It can be seen from Figure 9 that the high-pressure region of the bow shock increases with the increase of the blunt radius.



**Figure 7.** Pressure of blunted waverider along the center line (r = 10 mm).

### Characteristics of lift

Lift of waverider under different bluntness parameters is shown in Figure 10. It can be seen from Figure 10 that under the fixed blunt radius, the lift increases with the increase of parameter. With the fixed blunt radius from 2 mm to 10 mm, the increase amplitude of lift increases with the increase of parameter. The reason is that the normal projection area of blunt waverider increases with the increase of the parameter under fixed blunt radius. With the fixed blunt radius from 2 mm to 10 mm, the increase amplitude of normal projection area increases with the increasing of  $\lambda$  parameter. With the fixed  $\lambda$  parameter, the lift decreases with the increases of blunt radius. The reason is that the high-pressure leakage on the lower surface increases with the increase of blunt radius.

Pressure of blunted waverider in outlet plane is shown in Figure 11. The longitudinal coordinate is pressure coefficient  $C_p$  normalized by  $\rho_{\infty}^2 v_{\infty}^2/2$ .



**Figure 8.** Pressure contours of blunt waverider in symmetrical plane (r = 10mm) (a)  $\lambda = 0$ ; (b)  $\lambda = 1$ .

The abscissa coordinate is the direction of the width of the blunted waverider normalized by the maximum width  $W_{max}$  (0.744 m). The maximum width is the maximum width of the waverider under different bluntness parameter. The pressure distribution trend of waverider under different  $\lambda$  is similar. With the increase of the parameter  $\lambda$ , the difference between the maximum pressure and the minimum pressure increases. The lower surface of the blunted waverider is almost the same when y/W<sub>max</sub> is less than 0.5. The pressure decreases with the increase of  $\lambda$  parameter. The pressure in the blunt arc region of the blunted waverider increases with the increase of  $\lambda$  parameter.

Pressure contours of different blunt methods waverider in bottom plane (r = 10mm) are shown in Figure 12. With the increase of  $\lambda$  parameter, the



Figure 10. Lift of waverider under different bluntness methods.



**Figure 9.** Pressure contours in symmetric plane of waverider ( $\lambda = 1$ ) with different blunt radius (a) blunt waverider with symmetric plane; (b) pressure contour in symmetric plane of waverider; (c) r = 2mm; (d) r = 10mm.



**Figure 11.** Pressure of blunted waverider in outlet plane (r = 10 mm).



**Figure 12.** Pressure contours of different blunt methods waverider in bottom plane (r = 10mm).

high-pressure area on the lower surface gradually reduces and the high-pressure leakage area increases. In this part, the pressure contours with  $\lambda = 0$  and  $\lambda = 1$  are compared. The results show that when the coefficient  $\lambda = 1$ , the area of high-pressure leakage is larger. This study can provide theoretical basis for engineering application of waverider.

Pressure contours of blunt waverider in bottom plane ( $\lambda = 1$ ) are shown in Figure 13. The pressure distribution of the waverider is similar under different blunt radius. However, with the increase of blunt radius, the high-pressure area on the lower surface gradually reduces and the high-pressure leakage area increases.



**Figure 13.** Pressure contours of blunt waverider in bottom plane ( $\lambda = 1$ ).

### Characteristics of lift-to-drag ratio

Lift-to-drag ratio of waverider under different bluntness methods is shown in Figure 14. Under the fixed blunt radius, the lift-to-drag ratio decreases with the increase of the  $\lambda$  parameter. With the fixed blunt radius from 2mm to 10mm, the decrease amplitude of lift increases with the increase of coefficient. It is mainly induced by the difference of wetted area of the lower surface.

# Effect of volume

Volume of waverider under different bluntness parameters is shown in Figure 15. With the fixed blunt radius, the volume increases with the increase of the parameter. When  $\lambda = 0$ , the volume decreases with the increase of blunt radius. When  $\lambda = 1$ , the volume increase with increasing of blunt radius. An interesting phenomenon appears that when  $\lambda = 0.2$ , the volume remains constant with the increase of blunt radius. The volume increases with the increase of blunt radius while the parameter varies from 0.4 to 0.8.

Relationship between volume and lift to drag ratio of different bluntness parameters is shown in Figure 16. The volume and the lift to drag ratio are in weak positive proportion under "reducing material method" (the parameter in Figure 16 is 0). However, with the increase of  $\lambda$ , the relationship between lift-to-drag ratio and volume becomes more and more obvious in negative proportion. There is a critical parameter (0.2 in this case), that is, the change of blunt radius only leads to the change of lift-to-drag ratio, and the volume changes little.



Figure 14. Lift-to-drag ratio of waverider under different bluntness parameters.



**Figure 15.** Volume of waverider under different blunt parameters.



Figure 16. Relationship between volume and lift to drag ratio of different bluntness parameters.

When the parameter  $\lambda$  is introduced, the volume and other boundary parameters of the blunt waverider remain unchanged, but the adjustment scope of the aerodynamic parameters is greatly increased. Considering the different requirements of the airbreathing hypersonic aircrafts for the balance of thrust and drag, lift and weight, a suitable bluntness parameter can be selected to achieve a balance. In addition, because the scale of the waverider is relatively small in this paper, the influence of parameters on volume is limited. With the scale of the waverider increases (for example, the length of the aircraft is generally 50m-60m or even longer), the influence of the parameter on the volume will be more obvious.

### Conclusion

In this paper, a new bluntness method is proposed and the influence of different bluntness parameters on the aerodynamic performance of waverider is studied by computational fluid dynamics method. Some conclusions can be obtained:

- 1. With the angle of attack from 0 to 10 degree, the maximum lift-to-drag ratio of waverider with sharp leading edge is 5.19 when the angle of attack is 2 degree.
- 2. With the fixed blunt radius, the drag, lift and lift drag ratio of blunt waverider increases with the increase of the parameter  $\lambda$ . The high pressure non-uniformity and high-pressure leakage of the lower surface also increase with the increase of  $\lambda$ . With  $\lambda$  is given, the drag of blunt waverider increases with the increase of blunt radius, but the lift, lift-to-drag ratio of blunt waverider decrease with the increase of blunt radius. This research can provide guidance for the configuration design of blunt waverider.
- 3. The volume and blunt radius, lift drag ratio are in weak positive proportion. However, with the increase of the parameter  $\lambda$ , the relationship between the volume and the blunt radius, lift-to-drag ratio becomes more and more obvious in negative proportion. There is a critical parameter ( $\lambda = 0.2$ ), that is, the volume changes little with the increase of blunt radius, lift-to-drag ratio.
- 4. When the parameter  $\lambda$  is introduced, the volume and other boundary parameters of the blunt waverider remain constant, but the adjustment scope of the aerodynamic parameters is greatly increased.

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