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Research on the drag reduction performance induced by the counterflowing jet for waverider with variable blunt radii

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A B S T R A C T

Waverider will endure the huge aero-heating in the hypersonic flow, thus, it need be blunt for the leading edge. However, the aerodynamic performance will decrease for the blunt waverider because of the drag hoik. How to improve the aerodynamic performance and reduce the drag and aero-heating is very important. The variable blunt radii method will improve the aerodynamic performance, however, the huge aero-heating and bow shock wave at the head is still serious. In the current study, opposing jet is used in the waverider with variable blunt radii to improve its performance. The three-dimensional coupled implicit Reynolds-averaged Navier-Stokes(RANS) equation and the two equation SST k–ω turbulence model have been utilized to obtain the flow field properties. The numerical method has been validated against the available experimental data in the open literature. The obtained results show that the L/D will drop 7–8% when R changes from 2 to 8. The lift coefficient will increase, and the drag coefficient almost keeps the same when the variable blunt radii method is adopted, and the L/D will increase. The variable blunt radii method is very useful to improve the whole characteristics of blunt waverider and the L/D can improve 3%. The combination of the variable blunt radii method and opposing jet is a novel way to improve the whole performance of blunt waverider, and L/D can improve 4–5%. The aperture as a novel way of opposing jet is suitable for blunt waverider and also useful to improve the aerodynamic and aerothermodynamic characteristics of waverider in the hypersonic flow. There is the optimal P_{0in}/P_0 that can make the detached shock wave reattach the lower surface again so that the blunt waverider can get the better aerodynamic performance.

1. Introduction

Interest in the development of various types of hypersonic vehicles has been kept for several decades. One type of vehicles that are promising for hypersonic flight is the waverider, which first proposed by Nonweiler [1] in 1959. Waverider is a lifting body derived from a known analytical flow field such as flow around a cone and designed analytically with an infinitely sharp leading edge for shock-wave attachment. The attached shock wave can act as a barrier in order to prevent spillage of higher-pressure airflow from the lower side of the vehicle to the upper side, thus generate a high lift-to-drag (L/D) at a high Mach number [2]. At the same time, the waverider can break the "L/D barrier" which is proposed by Kuchemann [3] for hypersonic aircrafts. Therefore, the waverider is a good candidate for hypersonic flight [4–10]. Nowadays, there have been some remarkable vehicles which are designed based on waverider configuration, such as X-51A [11] and HTV-2.

However, it is extremely difficult to construct a perfectly sharp leading edge to achieve the attached shock-wave. Any manufacturing error will result in a significant deviation from the design contour. The sharp leading edge is not only difficult to maintain in the hypersonic flight condition, but also is difficult in manufacturing technology and impossible to achieve in practice. Thus, the leading edge should be blunt for heat transfer, manufacturing and handling concerns for practical hypersonic configurations [12]. Because a blunt leading edge promotes shock-wave standoff, shock detachment will occurs, making leading-edge blunting a major concern in the design and research on flowfield over hypersonic blunt waveriders. At the same time, the blunt leading edge will result in the drag increase, and there is a strong aero-heating along the leading edge at hypersonic flight speeds. For this, many researches had been done to improve the aerodynamic performance of blunt waverider. The experiment that Gillum and Lewis [13] had done for AEDC waverider showed that the $(L/D)_{max}$ of waverider reduces 19.74% with the blunt leading edge. The numerical

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investigation of Cao and Li [14] also showed that bluntness has a great effect on its aerodynamic performance, especially the drag and L/D. And, the impact of bluntness on the aerodynamic and aero-heating performance of waverider was taken into account synthetically by Santos [15,16] and Chen [17,18]. Their results showed that aerodynamic performance and aero-heating are highly sensitive to the bluntness of waverider. Starkey [19] made a study on the performances of a 22 m osculating cone-based waverider with different blunt radius, and the results implied that there could be an intermediate design point with a good balance between the vehicle aerodynamic and aero-heating concerns. Vanmol and Anderson [20] had defined the blunt radius varied in the span direction and studied the heat transfer characteristics for waverider. They suggested a formula to get the minimum leading edge radius based on the low density effects. Numerical and experimental studies were developed on waverider with blunt leading edge by Liu [21,22] at Ma = 10. The aerodynamic performance and aero-heating characteristics for blunt waverider were also taken into account together. At the same time, Liu proposed the "non-uniform blunt waverider" that improve the aerodynamic performance effectively. Though the influence of bluntness on the performance of waverider configuration has been studied deeply, the hypersonic flight tests were frequently abortive in recent years, such as HTV-2. That is because of the serious aero-heating along leading edge. So, how to reduce the drag and aero-heating effectively is still a key aspect for blunt hypersonic vehicle. There are so many work need to be done about the blunt waverider before its successful application. On the other hand, the opposing jet at the head of blunt body is an effective method to reduce the drag and aero-heating [24–30], and Huang [31,32] gave a detailed review on the drag and heat flux reduction induced by the counterflowing jet and its combinations. The blunt waverider geometry in the head is similar with the blunt body, thus, the opposing jet will work in the part of head to achieve the drag and aero-heating reduction.

In order to improve the aerodynamic performance of blunt waverider, the "non-uniform blunt radii method" will be used in this article. More, the opposing jet will also be used in the waverider with variable blunt radii to improve the aerodynamic performance and aero-heating characteristics deeply. The combination of non-uniform blunt radii method and opposing jet in the waverider is a novel way to make the waverider having the better characteristics. At the same time, the work will achieve a small step for transforming ideal waverider to practical application.

2. Design approach

2.1. The design method for cone-derived waverider

Waverider configurations have been constructed from axisymmetric flow fields past circular cones based on the theory that Kim and Rasmussen [33] provided. In the paper, the coordinate system and nomenclature are shown in Fig. 1, and a parabolic upper surface trailing edge is given, see Eq. (1). Then, the leading edge can be obtained along the free flow anti-direction in the shock-wave cone, according to Eq. (2), and at last, the trailing edge curve will be generated based on the relationship between R_{cb} and $R_{\infty b}$, see Eq. (3). Where, the waverider configuration is decided by the following parameters: Free stream Mach Number(Ma), Semi-vertex shock angle (β), Dihedral angle (ϕ_l) and Base body length (l). The upper surface is obtained by the rules of being parallel to the free stream. And the lower surface is generated by tracing streamlines from leading edge to the base plane.

$$X \equiv R_0 + AY^2 \tag{1}$$

$$Z = \sqrt{X^2 + Y^2} \bullet \cot(\beta) \tag{2}$$

$$R_{cb}^2 = \left(1 + \frac{\sigma^2 - 1}{\sigma^2} R_{\infty b}^2\right) \tag{3}$$

$$\sigma \equiv \frac{\beta}{\delta} \simeq \left[\frac{\gamma - 1}{2} + \frac{1}{K_\delta^2}\right]^{\frac{1}{2}} \tag{4}$$

According to the above theory, the basic waverider configuration was obtained and is summarized in the Table1.

2.2. The variable blunt radii method

In the article, the traditional blunt method is adopted to modify

Table 1
Design parameters for cone-derived waverider.

Design parameters	Values
Ma	8
β (°)	13.5
ϕ_l (°)	50
l (m)	1.0
l_w (m)	0.6

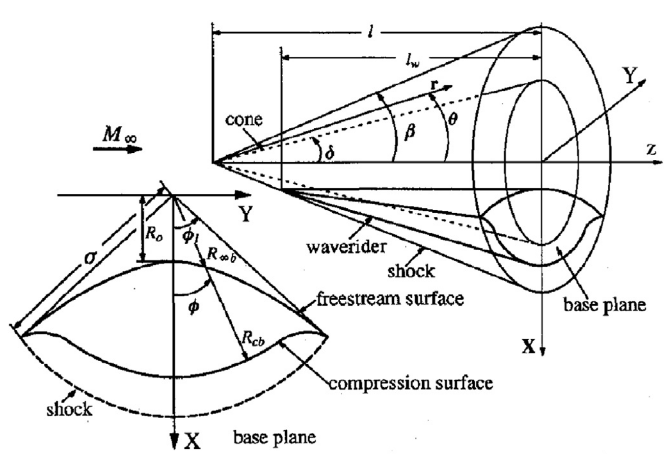

Fig. 1. Cone-derived waverider theory and coordinate system.