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Modification of hypersonic waveriders by vorticity-based boundary layer displacement thickness determination method

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ARTICLE INFO

Article history:
Received 27 September 2017
Received in revised form 11 December 2017
Accepted 12 December 2017
Available online xxxx

Keywords:
Hypersonic waverider
Viscous interaction
Displacement thickness
Effective shape
Vorticity

ABSTRACT

For general hypersonic vehicles flying at high altitudes and Mach numbers, the appearance of the large boundary layer displacement thickness can change the pressure distribution and aerodynamic characteristics significantly. As for the waverider, another side effect is that the shock wave position is deflected downward evidently even at the design Mach number, which is adverse for the shock wave being attached to the leading edge and may lead to more leakage of high pressure gas from the lower surface onto the upper surface. Therefore, this paper first develops a vorticity-based method to determine the boundary layer displacement thickness, in combination with the tangent wedge/cone method. Then, trying to alleviate the high pressure gas leakage near the leading edge, modification of a viscous optimized waverider is conducted under the condition of strong viscous interaction, by deducting the corresponding boundary layer displacement thickness from the original lower surface along the normal direction. Results show that the shock wave position around the lower surface of the modified waverider under the condition of strong viscous interaction is very close to that of the inviscid basic flowfield around the original waverider, which means less leakage of high pressure gas. But it's found that such change has little influence on the aerodynamic characteristics of the upper surface. However, an interesting discovery is that due to the lower pressure near the leading edge of the modified lower surface, the wave drag is lowered for the same lift, thus the lift-to-drag ratio is improved. The modified waverider also exhibits higher lift-to-drag ratio at large angles of attack when compared to waveriders with upper expansion surfaces. Overall, a vorticity-based boundary layer displacement thickness determination method is proposed in this paper, which is then used to modify waveriders to achieve higher aerodynamic efficiency.

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1. Introduction

High lift-to-drag ratio (L/D) is a key design objective for various kinds of hypersonic vehicles because higher L/D means higher down & cross range. For hypersonic flight characterized by large Mach numbers and high altitudes, the improvement of L/D is especially difficult due to the severe wave drag and friction drag. Kuchemann put forward a general empirical correlation for the maximum L/D based on data obtained from flight tests and experimental studies [1]:

$$(L/D)_{\max} = \frac{4(M_\infty + 3)}{M_\infty}$$

It shows that as the Mach number increases, an "L/D barrier" exists for the traditional aircrafts. To break this barrier, a previous design concept of waverider proposed by Nonweiler [2], drew researchers' attention. An idealized waverider is carved from an inviscid basic flowfield. In this approach, the shock wave is attached to the leading edge of the waverider, thus preventing the spillage of high pressure gas from the lower surface onto the upper surface and achieving excellent aerodynamic efficiency. However, the earliest 'caret' waverider, generated from a planar wedge flowfield by Nonweiler, presented very limited 'volumetric' efficiencies and severe 'aerothermodynamic leading edge' that rendered them unrealistic at that time. Moore and Jones et al. [3,4] extended the planar flowfield to the axisymmetric conical flowfield. Such cone-derived waveriders present better volumes because the concave streamlines are closer to the shock wave [5]. Kim and Rasmussen et al. [6] applied the calculus of variations to yield the optimum cone-derived waveriders with maximum L/D even when subjected to suitable engineering constraints. However, configurations opti-

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https://doi.org/10.1016/j.ast.2017.12.020
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Nomenclature

C_{eff}	effective shape determination coefficient
CL	lift coefficient
CD	drag coefficient
CD_{wave}	wave drag coefficient
CD_{fric}	friction drag coefficient
H	altitude
M	Mach number
p	pressure
T	temperature
u, v, w	velocity along the X, Y, and Z-axis
$\bar{V}'$	viscous interaction parameter
Xcp	relative location of the center of pressure
α	angle of attack
γ	ratio of the specific heats, 1.4
$\boldsymbol{\xi}$	vorticity
δ^*	boundary layer displacement thickness
β	shock wave angle
θ	deflection angle of body surface relative to the freestream direction
ρ	density

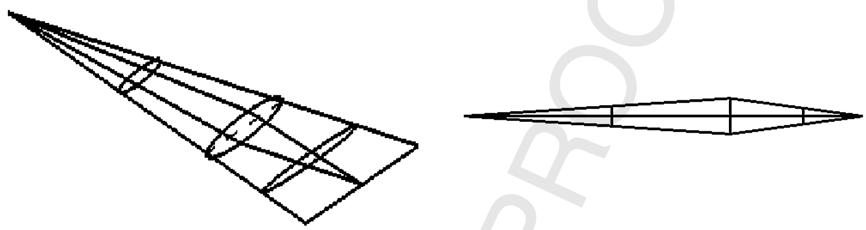

Fig. 1. All-body model.

mized by inviscid analysis are likely to have very large wetted areas and massive friction drag [7]. Therefore, they may perform poorly when viscous effects are taken into account. The skepticism for the aerodynamic characteristics of waverider is eliminated by the concept of viscous optimized waverider proposed by Bowcutt, Corda and Anderson [8,9], where viscous effects were included for the first time during the optimization process. Then the effects of chemically reacting flow and viscous interaction were further included in the optimization process [10]. The viscous optimized waveriders were also the first hypersonic configurations to break the aforementioned "L/D barrier". Since then, various kinds of waverider configurations are developed based on different basic flowfield [5,11–17]. A detailed overview of research on waverider design methodology is given by Ding et al. [18].

Potential application of waveriders for various hypersonic vehicles has also been widely discussed, including airbreathing hypersonic cruise vehicles [19], hypersonic entry vehicles [20], second stage for two-stage-to-orbit (TSTO) systems [21], and missions on other planets [22], etc. Before the application to realistic hypersonic vehicles, the waveriders must be studied thoroughly in various aspects, including off-design performance, aerothermal heating, stability and control, etc. For most researches, viscous effects are key factors that can seriously affect the theoretical performance of the waveriders. A number of problems may arise when viscous effects are taken into account, such as skin-friction drag, displaced shock, inviscid/viscous interaction in hypersonic regime [23]. Takashima studied a Mach 6 viscous optimized waverider by solving the three-dimensional Navier–Stokes (N–S) equations, demonstrating excellent on-design and off-design performance [24]. Viscous effects were also considered and studied by other literatures [7,25,26]. However, due to the relatively small Mach numbers, low altitudes and large waverider length-scale (30–60 m) focused on by most researchers, the viscous interaction is not strong enough to have an evident effect on the whole flowfield around the waverider. Under the condition of strong viscous interaction, the large boundary layer displacement thickness makes the effective shape differ from the original shape and changes the pressure distribution apparently [27]. Then a problem may be put forward: what effect will have on the aerodynamic characteristics of waverider by the obvious change of the effective shape? This paper tries to explore the above problem, in combination with a vorticity-based method to calculate the effective shape. Furthermore, an optimization method for the lower surface of waverider is presented based on boundary layer displacement thickness modification.

2. Computational-fluid-dynamics code validation

2.1. Numerical methods

An unstructured Computational-Fluid-Dynamics (CFD) solver GMFlow is used in this study [28]. A cell-centered finite volume method is employed to solve the three-dimensional compressible Euler or N-S equations. The AUSM+ spatial discretization scheme is adopted [29], with an implicit lower–upper symmetric Gauss–Seidel scheme for the temporal integration to accelerate convergence [30]. More details about the CFD solver can be found in [28, 31].

2.2. Validation

The experimental results of an all-body hypersonic aircraft model from [32] are used to validate the accuracy of the current CFD code. The model is shown in Fig. 1. The test conditions include: $M_\infty = 7.4$, $Re_{\infty,L} = 15 \times 10^6$ ($L = 0.9144$ m), $\alpha = 0, 5, 10, 15$ deg, $T_\infty = 62$ K and $T_w = 300$ K. The 3-equation k–ε–Rt turbulence model is adopted in the computations [33]. The effects of angle of attack on the windward and leeward centerline pressures are summarized in Fig. 2. For the windward side, good agreement is achieved between the pressures by the experiment and by the CFD code. The forebody pressures are slightly underpredicted at higher angles of attack, which is similar to those from the NASA Ames UPS code [32]. For the leeward side, good agreement is also obtained between the experimental and numerical results. The above results show that the current CFD code is reliable for the calculation of hypersonic aerodynamic problems.

3. Vorticity-based effective shape determination method

It's well known that for hypersonic flight, the high altitudes and large Mach numbers may lead to a thick hypersonic boundary layer, which displaces the outer inviscid flow and changes the

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Please cite this article in press as: W. Liu et al., Modification of hypersonic waveriders by vorticity-based boundary layer displacement thickness determination method, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2017.12.020

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