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Novel approach for design of a waverider vehicle generated from axisymmetric supersonic flows past a pointed von Karman ogive

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ABSTRACT

This paper proposes a novel waverider generated from axisymmetric supersonic flows past a pointed von Karman ogive. First, a pointed von Karman ogive is obtained by pointing the blunt nose of the original von Karman ogive. Then, the axisymmetric supersonic flow field past the pointed von Karman ogive is calculated using the method of characteristics, and this calculated flow field is employed as the new basic flow field of a waverider. A novel waverider is generated from this new basic flow field by a streamline tracing technique that is based on left-running Mach lines. Second, numerical methods are employed to validate the applicability of this new design concept to an aerodynamic configuration. Finally, a comparison model is designed using the conventional design concept and its performance is numerically predicted to analyze the differences between the new and conventional design concepts. The comparison results show that the novel waverider possesses higher lift-to-drag ratios, smaller trim drag, and larger internal volume than the conventional waverider; the results also demonstrate that the proposed design concept can provide greater flexibility in the design and optimization of hypersonic waverider vehicles.

1. Introduction

Hypersonic vehicles have become one of the key research areas in the field of aerospace engineering in the 21st century in view of the importance of long-range precision strike operations [12–14,16].

A waverider is any supersonic or hypersonic lifting body that is characterized by an attached, or nearly attached, oblique shock wave along its leading edge [21]. Previous studies have shown that a waverider can be designed to have features that may be advantageous as the basis for a hypersonic configuration [15]. Optimized waveriders have been confirmed to generate higher lift-to-drag ratios than comparable lifting bodies and can provide reasonable volumetric efficiency with minimal degradation of performance [3,30]. Computational fluid dynamics (CFD) studies have shown that optimized waveriders also have acceptable off-design performance [20,27].

In the past 50 years, researchers have widened the design space of a waverider by attempting to establish choices of basic flow fields from which the waverider is generated, and the aim of such studies has been to improve the aerodynamic performance of hypersonic vehicles, particularly their lift-to-drag ratio and volumetric efficiency. Basic flow fields can be classified into two types—axisymmetric and non-axisymmetric. In most of these studies, the basic flow fields were considered as axisymmetric flows for ease of calculation. Axisymmetric flows allow for rapid design of waveriders. Nonweiler [24], Jones et al. [18], Rasmussen [25], Corda and Anderson [5], and He et al. [11] first employed flows past a wedge, circular cone, elliptic cone, power-law body, and curved cone, respectively, as the basic flow fields to generate waveriders at a zero angle of attack. Further, Goonko et al. [10] and Mazhul [22] respectively used the convergent flow inside constricting ducts and an isentropic compression flow as the basic flow fields to generate waveriders. All the above-listed flows can be classified as axisymmetric flows. Takashima and Lewis [28] derived a non-axisymmetric flow field from a flow past a wedge-cone body and first used it as the basic flow field to generate waveriders.

The von Karman ogive [23] is one of the minimum-drag bodies of revolution at a zero angle of attack with supersonic speeds. Since the von Karman ogive offers minimum pressure drag for a given length and diameter, it is often used as the nose cone in the aerodynamic design of a rocket or missile. Then, one might intuitively speculate that a novel waverider with lower drag and higher

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Nomenclature

MOC	Method of characteristics
L_0	Length of von Karman ogive, m
R	Base radius of von Karman ogive, m
δ	Angle of slope, °
δ_A	Angle of slope at point A, °
θ	Flow angle, °
x	Axial coordinate, m
r	Radial coordinate, m
M_0	Free-stream Mach number
P_0	Free-stream static pressure
T_0	Free-stream static temperature
Ma	Flight Mach number
P	Local static pressure, Pa
P/P_0	Ratio of local static pressure to free-stream static pressure
R_S	Radius of shock wave at the base plane, m
α	Angle of attack, °
L'	Lift, N
D'	Drag, N
M'	Pitching moment, N·m
S_r	Reference area, m^2
l_r	Reference length, m
q_∞	Freestream dynamic pressure, Pa
C_L	Lift coefficient
C_D	Drag coefficient
C_{mz}	Pitching moment coefficient
L/D	Lift-to-drag ratio
L_W	Length of waverider, m
H_W	Height of waverider, m
Δ	Increment percentages of drag coefficient and lift-to-drag ratio due to the viscous effects, %
Vol	Internal volume of waverider, m^3
S_{wet}	Wetted surface area of waverider, m^2
S_p	Planform surface area of waverider, m^2
S_b	Base area of waverider, m^2
η	Volumetric efficiency

lift-to-drag ratio may be generated by using the flow past a von Karman ogive as the basic flow field. However, the von Karman ogive is a blunt body, and when it travels at a supersonic or hypersonic speed, the blunt nose will induce a detached shock wave and a subsonic flow field will form in the region surrounding the tip of the body. Therefore, it is important to modify the original von Karman ogive in order to obtain an acceptable aerodynamic configuration for hypersonic vehicles.

The method of characteristics (MOC) is the most accurate numerical technique for solving hyperbolic partial differential equations [31], and it can save computational cost. Therefore, in the design process of waveriders, the MOC is an effective approach for calculating the basic flow field when the flow is completely supersonic behind the shock wave [11,19].

In the present study, a novel waverider generated from axisymmetric supersonic flows past a pointed von Karman ogive is examined. This pointed von Karman ogive is obtained by pointing the blunt nose of the original von Karman ogive. Next, the axisymmetric supersonic flow field past the pointed von Karman ogive is computed using the MOC, and this flow field is employed as the new basic flow field of waveriders. Specifically, this new basic flow field is used to generate a novel waverider by using the streamline tracing technique. Finally, the novel waverider is validated using numerical approaches.

2. Novel waverider

2.1. Pointed von Karman ogive

Von Karman used the slender-body theory to obtain the minimum-drag ogive of a given length L_0 and base radius R at supersonic speeds; this is referred to as the von Karman ogive [23]. The contour of the von Karman ogive is computed from Eqs. (1) and (2) [8], and its schematic illustration is shown in Fig. 1. The distribution of the angle of the slope of the von Karman ogive along the x axis, denoted as δ, is shown in Fig. 2. The initial δ value at $x = 0$ is 90°. Thus, the head of the von Karman ogive is blunt. In other words, the von Karman ogive has a blunt nose. In order to ensure the creation of a completely supersonic flow with an attached shock wave when the ogive travels at a supersonic or hypersonic speed, a von Karman ogive with a pointed nose (hereafter simply called 'pointed von Karman ogive') is required.

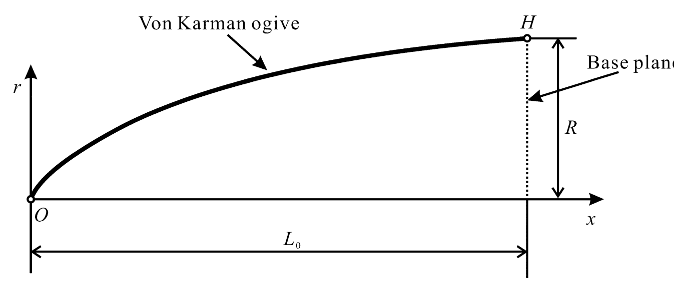

Fig. 1. Schematic illustration of von Karman ogive.

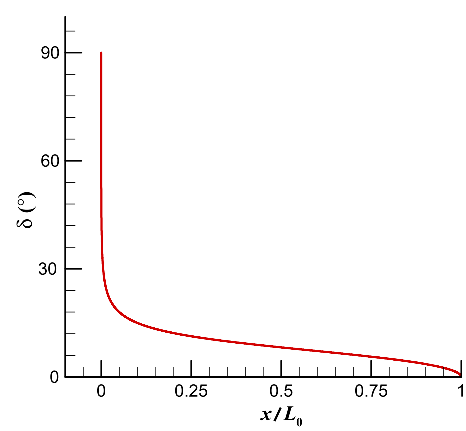

Fig. 2. Distribution of angle of slope of von Karman ogive along the x axis.

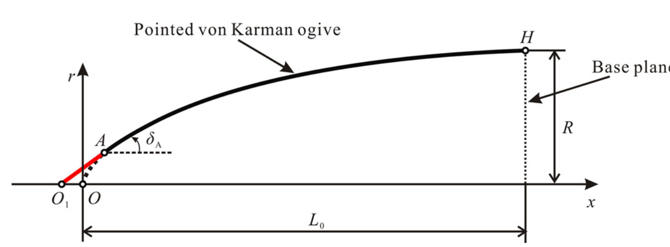

Fig. 3. Schematic illustration of pointed von Karman ogive.

A pointed von Karman ogive is obtained by pointing the blunt nose of the von Karman ogive. As shown in Fig. 3, the blunt nose contour *OA* of the von Karman ogive is replaced with a straight