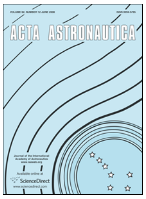
Acta Astronautica 108 (2015) 62–78

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro



# Influence of surface pressure distribution of basic flow field on shape and performance of waverider

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ARTICLE INFO

*Article history:*
Received 22 July 2014
Received in revised form
28 November 2014
Accepted 30 November 2014
Available online 11 December 2014

*Keywords:*
Hypersonic vehicle
Waverider
Basic flow field
Surface pressure distribution
Method of characteristics

ABSTRACT

This study investigates the influence of the surface pressure distribution of a basic flow field on the shapes and performances of waveriders. First, three axisymmetric basic flow fields having different surface pressure distributions but identical shock waves are designed and obtained using the method of characteristics (MOC). Second, three waveriders—increasing-pressure, constant-pressure, and decreasing-pressure waveriders—are generated from these three basic flow fields. Finally, numerical methods are employed to verify the design procedure of waveriders with different pressure distributions of the basic flow field and to analyze the differences between the three waveriders. The obtained results show that the surface pressure distribution of the basic flow field is an important factor in the design of waveriders. The waverider generated from the basic flow field having increasing surface pressure along the stream direction has a larger volume and lower lift-to-drag ratio. In contrast, the waverider generated from the basic flow field having decreasing surface pressure along the stream direction has a smaller volume and higher lift-to-drag ratio. Changing the surface pressure distribution of the basic flow field can lead to greater flexibility in the design and optimization of hypersonic waverider vehicles.

## 1. Introduction

A waverider is any supersonic or hypersonic lifting body that is characterized by an attached, or nearly attached, bow shock wave along its leading edge [1]. Previous studies have shown that a waverider can be designed to have features that may be advantageous as the basis for hypersonic configurations [2]. Optimized waveriders have been shown to generate higher lift-to-drag ratios than other comparable lifting body designs. They also provide reasonable volumetric efficiency with only minimal loss of performance [3,4]. CFD analyses have shown that optimized waverider shapes have acceptable off-design performances [5,6].

In the past few decades, researchers have widened the design space of a waverider by attempting to establish the types 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. In most of these studies, the basic flow fields were considered as axisymmetric flows for ease of calculation; axisymmetric flows are flows past axisymmetric generating bodies at a zero angle of attack with supersonic speeds. The most frequently

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http://dx.doi.org/10.1016/j.actaastro.2014.11.038
0094-5765/

**Nomenclature**

| | |
|---|---|
| MOC | method of characteristics |
| $L$ | length of basic flow field, m |
| $L_A$ | length of cone $OA$, m |
| $\delta_A$ | semi-vertex angle of cone, ° |
| $\delta$ | angle of slope, ° |
| $M_0$ | free-stream Mach number |
| $P_0$ | free-stream static pressure, N/m$^2$ |
| $T_0$ | free-stream static temperature, K |
| $T_{t,0}$ | free-stream total temperature, K |
| $Ma$ | flight Mach number |
| $P$ | local static pressure, N/m$^2$ |
| $P/P_0$ | ratio of local to free-stream static pressures |
| $R_S$ | radius of shock wave at the base plane, m |
| $\alpha$ | angle of attack, ° |
| $C_L$ | lift coefficient |
| $C_D$ | drag coefficient |
| $C_{mz}$ | pitching moment coefficient |
| $L/D$ | lift-to-drag ratio |
| $L_w$ | length of waverider, m |
| $W$ | width of waverider, m |
| $Vol$ | 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$^2$ |
| $\eta$ | volumetric efficiency |
| $\mu$ | viscosity coefficient, kg/(m s) |
| $k$ | thermal conductivity of gas, W/(m K) |
| $C_p$ | specific heat at constant pressure, J/(kg K) |
| Pr | Prandtl number |
| $C_f$ | skin friction coefficient |

used axisymmetric basic flow field is the flow past a cone, which was first employed by Jones et al. [7]; waveriders derived from this basic flow field possess a high lift-to-drag ratio and large volumetric efficiency. Corda and Anderson [8] and Mangin et al. [9], with the aim of achieving a higher lift-to-drag ratio and improving the carrying capacity of the waverider, generated it using the flow past a power-law body as the basic flow field. Further, He et al. [10], with the aim of meeting the requirement of air compression at the inlet entrance, first used the flow past a curved cone as the basic flow field to generate waveriders. It is worth noting that the pressure distribution over the surface of the generating body is constant, decreasing, or increasing along the stream direction for flow past a cone, power-law body, or curved cone, respectively. Then, one might intuitively speculate that the pressure distribution over the surface of the generating body may be an important factor in the design process of waveriders.

However, to the best of the authors' knowledge, the influence of the surface pressure distribution of the basic flow field on the shape and performance of waveriders has rarely been reported in the open literature, and it is a very important factor for the conceptual design of hypersonic vehicles in order to improve its overall performance. Therefore, in the current study, first, three axisymmetric basic flow fields having different surface pressure distributions are designed and produced. Then, the waveriders generated from these three basic flow fields are compared in order to examine the effect of the surface pressure distribution of the basic flow field on the shape and performance of these waveriders. The effect of the surface pressure distribution of the basic flow field on the heat flux distribution of waveriders will be discussed in the near future.

## 2. Design and generation of axisymmetric basic flow field

With the aim of analyzing the effect of surface pressure distributions on the shape and performance of waveriders in this article, three axisymmetric basic flow fields owning different surface pressure distributions along the stream direction are designed. The shock waves of the basic flow field play an important role in the design of waveriders. Then, to exclude their influence on waveriders, the shock waves of the three axisymmetric basic flow fields are designed to be identical.

As shown in Fig. 1, a conical shock wave $OS$ is formed when the cone $OA$ travels at the designed Mach number $M_0$ and zero angle of attack, and the cone can be defined in terms of length $L_A$ and semi-vertex angle $\delta_A$. A left-running Mach line $AS$ originating from point $A$ intersects with the conical shock wave $OS$ at point $S$. The cross section that passes through point $S$ is used as the base plane of the basic flow field. Given the parameters $M_0$, $L_A$, and $\delta_A$, the total length of the basic flow field ($L$) and the radius of the conical shock wave at the base plane ($R_s$) can be determined. Three body contours—$AH_1$, $AH_2$, and $AH_3$—join smoothly with the straight contour $OA$ at point $A$, and they are expressed by a second-order equation (i.e., Eq. (1)) in two dimensions of the cylindrical coordinate system shown in Fig. 1. The angles of slope at the ends of these three body contours are $\delta_1$–$\delta_3$, respectively, and the starting angle of the slope is equal to $\delta_A$. Given the parameters $\delta_1$–$\delta_3$, the three body contours can be determined, as can be the coefficients $a$–$c$ in Eq. (1). $\delta_1$–$\delta_3$ are larger than, equal to, and smaller than, respectively, $\delta_A$; therefore, the corresponding body contours $AH_1$–$AH_3$ are concave, straight, and convex, respectively. When $OAH_1$–$OAH_3$ travel at the designed Mach number $M_0$ and zero angle of attack, three axisymmetric flows are obtained, and the surface pressure distribution after point $A$ along the stream direction is increasing, constant, and decreasing, respectively (see Fig. 2). Fig. 2 shows the specific surface pressure distributions of these three axisymmetric flows. All three flows have the same conical shock wave $OS$ because the three bodies have the same cone contour $OA$. The specific parameters of the axisymmetric bodies $OAH_1$–$OAH_3$, as well as the properties of the free-stream flow, are listed in Table 1.

According to the basic philosophy of waverider [11], any waverider configuration is designed on the basis of inviscid flow fields. Further, any waverider shape is carved