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A parametric study on the aerodynamic characteristics of a hypersonic waverider vehicle

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ABSTRACT

Hypersonic waverider vehicles with a high lift-to-drag ratio have drawn an ever increasing attention. In this paper, a parametric analysis method has been employed to investigate the effects of the angle of attack, angle of the sideslip and the inflow Mach number on the aerodynamic performance of the vehicle by numerically solving the governing fluid flow equations for the flow field around a hypersonic slender cone. The results obtained show that the flow field around the investigated hypersonic vehicle can satisfy the aerodynamic requirements of the vehicle. At larger angles of attack, the ratio of the lift-to-drag of the vehicle is higher among the range considered, and it will be advantageous for vehicles that cruise at smaller angles of attack. Changing the angle of the sideslip can have a significant impact on the lateral performance of the vehicle; however, its effects on the drag and lift of the vehicle are very limited. On increasing the inflow Mach number, the aerodynamic performance of the vehicle improves for the range of Mach numbers considered. This investigation provides researchers with guidelines for the optimization of the design of this class of vehicle.

1. Introduction

Near space is generally defined as the blank region between 20 and 100 km, including a majority of regions in the stratosphere, the mesosphere and partial regions in the thermosphere, and this environment cannot support the vehicle with enough air to cruise for a long time. Recently, the strategic value of the near space has drawn an ever increasing attention of many countries, and the research on the near-space aircraft has substantially increased [1]. In order to satisfy the high aerodynamic requirement of the near space, many kinds of aircraft configuration have been brought forward, namely the lift body and waverider. In 1959, Nonweiler [2] brought forward the waverider flying concept for the first time. With the success of the Hyper-X project [3,4] and the first flight test of X-51A on May 26, 2010 [5], the investigation of hypersonic vehicles has drawn an ever increasing attention of researchers worldwide. The hypersonic waverider vehicle with a high lift-to-drag ratio is one of the most promising aerodynamic configurations for future hypersonic vehicles [6], and how to design their configurations and obtain their aerodynamic performances has become one of the most important key developments in recent years. At the same time, the atmospheric environment has a large impact on the aerodynamic characteristics of the hypersonic vehicle, and how to maintain high

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performance out of the cruising phase is the primary point of interest for researchers.

The aerodynamic advantage of the waverider is that the high pressure behind the shock wave under the vehicle does not "leak" from around the leading edge to the top surface, such that the lift-to-drag ratio (L/D) for the waverider is considerably higher than that for a conventional aerodynamic vehicle, and this is beneficial for the vehicle to cruise for a longer time in the near space. Moreover, waveriders yield flow fields and aerodynamic properties that can be accurately worked out for some particular on-design conditions which provide reliable baselines over a wide range of Mach numbers and configuration geometries. This allows a systematic optimization of the parameters that are pertinent to the design process [7].

The waverider is composed of three surfaces. The upper one is called the free stream surface, and the lower one is called the base plane. The curve where the base plane intersects the free stream, or compression surface, is called the trailing-edge curve [8].

A number of researchers have theoretically investigated the aerodynamics of waverider vehicles. For example, Zhang et al. [9] studied the design parameters of waveriders with various wedge angles, and including viscous effects, and they investigated the effect of the design parameters on the aerodynamics of the vehicle. Further, Mangin et al. [10] compared the flow field around axisymmetric bodies of the waveriders with those obtained using a method based on an Eulerian code and those generated by the Taylor–Maccoll system and inviscid hypersonic small-disturbance theory.

This paper discusses the effects of the angle of attack, angle of the sideslip and the inflow Mach number on the aerodynamic performance of the hypersonic waverider vehicle designed through the flow field of a hypersonic slender cone.

2. Design of the waverider

2.1. The design of the flow field

The shape of the conical shock wave is determined by solving the flow field of the hypersonic slender cone approximately, see Fig. 1, and its conical angle is calculated using the following expression [11]:

$$\frac{\beta}{\omega_k}=\frac{\gamma+1}{\gamma+3}\left[1+\sqrt{1+\frac{2(\gamma+3)}{(\gamma+1)^2M_\infty^2\omega_k^2}}\right] \tag{1}$$

where β is the angle of the shock wave, ω_k is half of the benchmark shock wave angle, M_∞ is the free stream Mach number and γ is the ratio of the specific heats for the boundary condition.

In the coordinate system adopted, the z-axis is used to design the conical shock wave, which is in the direction of the inflow. The y-axis is in the spanwise direction used to design the configuration, and the x-axis is determined by the right-hand screw rule. For convenience, the apex of the conical shock wave is chosen as the origin of the coordinate system. There are two methods to design the flow field, namely begin with a free stream surface or with a compressed stream surface. The difference between the two methods is in the definition of the baseline in the base surface. The first method defines the baseline in the base surface as the intersecting line of the free stream surface and the base surface of the conical shock wave. When the baseline in the base surface is determined, based on the geometric relation that the upper surface should be parallel to the inflow direction, the location of the leading edge can be calculated along the inflow direction, which is the intersecting line of the upper surface and the conical shock wave. Further, the lower surface should be parallel to the streamline after the shock wave, then the lower surface can be traced point-by-point along the streamline, starting from the leading edge, and the bottom baseline of the lower surface is generated. Thus the primary design of the configuration is completed. The design sequence can be noted as $A>B>C$. In the second method, the bottom baseline is the intersecting line between the compressed surface and the base surface of the conical shock wave, its design procedure is completely the opposite to that of the first method, i.e. its design sequence is $C>B>A$. The basic geometric designs ascertained on the upper and lower surfaces of the waverider configuration are similar when using these two methods. The coordinate relation between points can be generated using geometric relations [13].

This paper uses the above described first method since the geometric relations are simpler compared with those in the second method, namely the design of the vehicle begins with the free stream surface. Starting from an arbitrary point (x_1, y_1, z_1) on the bottom baseline, the corresponding coordinate point (x_2, y_2, z_2) at the leading edge can be calculated using a forward geometric relation in which the free stream surface is parallel to the inflow

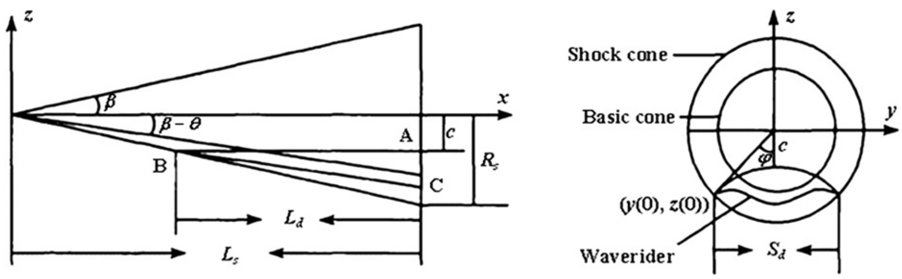

Fig. 1. Configuration design of a typical waverider vehicle [12].