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Design and experimental study of a practical Osculating Inward Cone Waverider Inlet

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Abstract A design method based on tip to tail streamline tracing and osculating inward cone methods is discussed for designing the integrated Osculating Inward Cone Waverider Inlet (OICWI). A practical geometrical constrained experimental model of OICWI is designed based on the validated design method. It has a total contraction ratio of 4.61 and inner contraction ratio is 2.0. Wind-tunnel tests have been conducted for the OICWI model at free stream Mach number (Ma_∞) of 4.0, 3.5 and 3.0 respectively. The experimental results show that the OICWI has high flow capture ratio and compression abilities. It can self-start at $Ma_\infty = 3.5$ and 4.0 and its flow capture ratio is 0.73 at $Ma_\infty = 4.0$, and Angle of Attack (AOA) 0°. The research results show that the OICWI has advantages of inward cone waverider and streamline tracing inlet. Present OICWI is a novel approach for waverider inlet integration studies and it will promote the use of waverider inlet integration configuration in the studies of airbreathing hypersonic vehicles.

1. Introduction

Hypersonic vehicles with airbreathing propulsion have been studied intensively in recent years. One of the difficulties of airbreathing hypersonic flight is the decreasing thrust to drag margin when the vehicle's speed increases. From aerodynamic view, increasing the vehicle's lift to drag ratio and inlet captured mass flow rate will reduce vehicle's drag and increase its propulsion force.

Waveriders[1–4] are the most suitable options for those high lift to drag ratio vehicles, but there are several shortcomings of waveriders from the engineering lever view,[5] such as low volumetric capacity and low flow compression ability. Waverider's unconventionally curved compression surface makes it difficult to integrate with all kinds of inlets.

On the other hand, hypersonic inlets with high performances can be designed by using sophisticated design methods.[6–10] However, it is difficult for them to integrate with vehicle's forebody. By using geometric modification techniques during the integrations, the disturbed incoming flow caused by vehicle's forebody will decrease the inlet's high performance.[11,12] Considering the low thrust to drag margin of the hypersonic airbreathing vehicles, the decreased performance

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caused by the improper integrations of forebody and inlet should not be ignored. One of the most urgent tasks now is to devise a practical method to design the waverider and inlet as a whole.

O'Neill and Lewist[13] used conically derived waverider as forebody. The inlet's cowl surface is established by streamlines traced from conical flow field. The inlet is presumed to be a two-dimensional planar flow. Takashima and Lewis,[14] and O'Brien and Lewis[15] used osculating cone waverider[1] as forebody. The forebody has a planar portion around center line that generates a uniform wedge flow field. The flow traverses a series of three wedge compression ramps of equal compression angle before entering the combustor.[15] Starkey and Lewis[16] used analytical variable wedge angle method to generate waverider forebody which has a planer portion in the middle of waverider. The inlet used three successive compression ramps and integrated with a forebody as same as Refs. 14,15. You et al.[17] proposed a dual waverider design concept for forebody-inlet integration in the spanwise direction. Li et al.[18] furthered You's work and considered the double flow paths in the dual waverider forebody-inlet integration. The abilities of anti-backpressure and start/restart of hypersonic inlet are also very important aspects, and there have been many papers devoted to the investigation on it. Chang et al. studied the unsteady behavior of hypersonic inlet unstart flow caused by back pressure, and found two novel inlet unstart patterns[19] and one new local unstart pattern.[20] The unstart/restart characteristics of hypersonic inlet and mathematical modeling on hypersonic inlet buzz have been studied by Chang et al.[21,22], and the unstart prediction and detection methods to prevent inlet unstart have also been studied. Trapier et al.[23] gave some detailed analysis of supersonic inlet buzz, and the start and restart characteristics of a typical supersonic buzz are well studied in their paper.

For the integration design of hypersonic forebody and inlet, most of the studies introduced above are still in conceptual design phase. The complex aerodynamic characteristics of the integrated forebody inlet, such as flow field structures, flow capture abilities and inlet combustor matching requirements, should be studied intensively and the validity of the design method should be proved experimentally.

Since inward turning inlet[6,7] and inward waverider[3] are all derived from inward turning cone flow fields, great interests have been aroused for combining the inward turning waverider and inlet as a whole system. The objective of this paper was to present a methodology for the design of integrated Osculating Inward Cone Waverider Inlet (OICWI), and provide experimental study results of the designed OICWI at Mach 4.0, 3.5 and 3.0. The paper is organized as follows: in Section 2, the design methodology and experimental model under geometrical constraints are designed. Section 3 discusses the experimental facilities and experimental setup. Section 4 discusses experimental results and performance of the OICWI. The OICWI's performance is characterized by self-restart ability, mass flow rate, and anti-backpressure ability. Finally, Section 5 offers some concluding remarks.

2. Design methodology and its application

2.1. Overview of design methodology

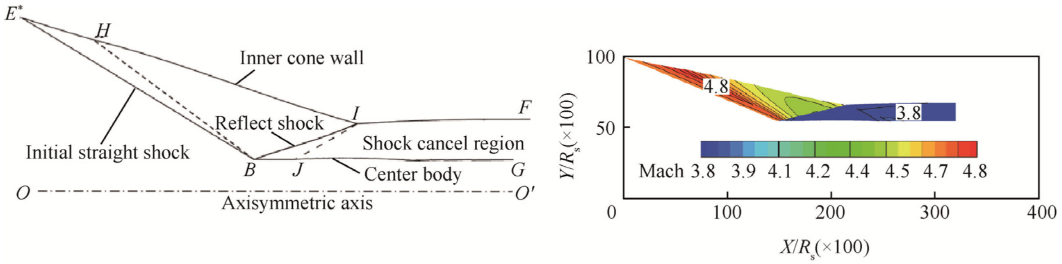
The design methodology of OICWI and its validation have been reported by the authors in their previous paper.[24–26] The design method is introduced briefly here with the refined figures and new design parameters.

The design of the OICWI is based on basic inward turning flow field. Its outer compression part (Region BE^*I) and inner compression part (Region $BIFG$) are shown in Fig. 1(a). The Method of Characteristics (MOC) is used as design tool for designing the basic flow field. In basic flow field's outer compression part BE^*I, only a part of Internal Conical Flow A[27,28] (Region BE^*H) is used to generate a straight initial compression shock. Curved inward turning cone wall HI is tangent to E^*H at point H and shape of HI can be regulated to control the basic flow field's outer/inner compression ratio.

In inner compression part ($BIFG$), shape of cone wall (IF) is defined by quadratic curve which is tangent with the flow angle at point I. The Mach number on point F is defined and it is smoothly distributed on the curve IF from point I to point F. Shock cancel technique[29] is used to eliminate shock reflection on inner cone wall IF. Center body shape JG is determined by matching mass flow rate on each characteristic originated from IF.

In the present basic flow field, design Mach number is 6. Initial shock wave angle is 17°. Center body radius at point B is 55% of the radius at E^*. Mach number at point F is defined as 3.8. Total and inner compression ratios of the basic flow field are 4.5 and 1.85 respectively. The basic inner cone's flow field is calculated by MOC and its Mach number contour is shown in Fig. 1(b). OO' is axisymmetric axis of the basic flow field. X and Y are the basic flow fields' coordinate and R_s is the radius at point E^*.

Osculating inward turning cone[28] and tip to tail streamline tracing methods are used in the OICWI method. In the



(a) Basic flow field's structure

(b) Mach number contour

Fig. 1 Schematic diagram of basic flow field.