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 ($M_a$) 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 $M_a = 3.5$ and 4.0 and its flow capture ratio is 0.73 at $M_a = 4.0$, 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.

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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 are the most suitable options for those high lift to drag ratio vehicles, but there are several shortcomings of waveriders from the engineering lever viewpoint, 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. 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. Considering the low thrust to drag margin of the hypersonic airbreathing vehicles, the decreased performance...
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 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 Lewis15 used osculating cone waverider 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 Lewis16 used analytical variable wedge angle method to generate waverider forebody which has a planar 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 patterns19 and one new local unstart pattern.20 The unstart/restart characteristics of hypersonic inlet and mathematical modeling on hypersonic inlet buzz have also been studied. Trapier et al.23 gave some detailed analysis of supersonic inlet buzz, and found two novel inlet unstart patterns caused by back pressure, and two novel unstart/restart characteristics of hypersonic inlet buzz have been studied by Chang et al.21 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 inlet6,7 and inward waverider3 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’HI) is used to generate a straight initial compression shock. Curved inward turning cone wall H’I is tangent to E’H at point H and shape of H’I 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 technique29 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 is the radius at point E’.

Osculating inward turning cone28 and tip to tail streamline tracing methods are used in the OICWI method. In the
OICWI's cowl leading edge plane, shown in Fig. 2(a), Inlet Capture Curve (ICC) is defined by super-ellipse curve:

\[
\begin{align*}
    x &= L_x (\cos \theta)^{2/n} \\
    y &= L_y (\sin \theta)^{2/n}
\end{align*}
\]

where \( L_x \), \( L_y \), and \( \theta \) are used to define ICC's shape and size. Front Capture Tube (FCT) is generated by parabolic curve.

In the cowl leading edge plane, ICC’s curve’s center will be found firstly. For example, for point A on ICC, its corresponding curve center \( A \) is found. Points \( B \) and \( A \) generate an osculating plane \( AB \). In oscillating plane \( AB \), there are some corresponding relationships between oscillating plane \( AB \) (Fig. 2(a)) and the basic flow field (Fig. 2(b)). In Fig. 2(a), point \( A \) corresponds to the basic flow field’s axisymmetric center and point \( B \) corresponds to the intersection point between the basic flow field’s initial shock and center body. Point \( D \) is the intersection point between oscillating plane \( AB \) and the FCT.

As the basic flow field is scaled and matched with the corresponding points in the oscillating plane \( AB \) (Fig. 2(b)), a horizontal line starting from point \( D \) will intersect with the initial shock \( E' \) at \( D' \). A streamline which starts from point \( D' \) is traced in the basic flow field until it exits. And this tip to tail streamline is used to construct the body side’s compression surface in the oscillating plane \( AB \). The corresponding inlet cowl surface in oscillating plane \( AB \) is generated by the center body curve \( BG \). Repeating the above procedures along ICC line point by point, the OICWI's compression surface on body and cowl sides can be constructed.

In practical implementation, only center part of ICC curve is used as inlet capture section, and corresponding inlet capture area is \( \text{BB'} \text{DD'} \). Inlet’s side walls are constructed by the osculating planes such as \( \text{BC} \) and \( \text{B'C} \). Fig. 2(c) shows the designed prototype OICWI, and the corresponding points in Fig. 2 (a) and (b) are shown in Fig. 2(c).

Previous forebody/inlet integration design method generally has three steps. Forebody is designed firstly and then inlet is designed. The inlet and forebody are integrally designed by geometric merging tools. The disadvantages of the previous design method have been described above such as decreased inlet's performance caused by disturbed incoming flow and large flow spillage under design condition, and the flow field structures of forebody and inlet are not exactly matched with each other even under design condition.

The advantages and innovation points of present OICWI method are as follows: forebody and inlet are designed as continuous stream surfaces at the same time and there is no geometric modification on their junction surfaces during the integration procedures. The integrated forebody and inlet have high performance with few flow spillages especially under design condition and its flow field structures match with the basic flow field structures well. The waverider and inlet's flow field are not disturbed by the integration procedures and they will remain their original high lift to drag ratio and qualified compression abilities. The disadvantage of present OICWI is its relatively low volume characteristics caused by its concave forebody shape. This shortcoming can be overcome by using the outer cone as the basic flow field. This improved design method has been investigated and will be reported soon.

### 2.2 Design of geometric constrained practical OICWI

Based on the prototype OICWI designed in Section 2.1, an OICWI experimental model is generated under practical considerations. Parts of the prototype's forebody (Fig. 2(c)) are truncated, but its whole compression surface from forebody leading edge to inlet throat is remained. Fig. 3(a) is three-dimensional view of the experimental model. It has a maximum forebody width of 0.15 m. Its length is 0.297 m from its leading edge to cowl lip and 0.63 m to isolator exit. Its capture area is \( 7.326 \times 10^{-3} \text{ m}^2 \), and throat area is \( 1.690 \times 10^{-3} \text{ m}^2 \). Its total compression ratio is 4.6 and inner compression ratio from the cowl lip to the throat is 2.0. Its side walls at the beginning of inner compression parts are cut off from its leading edge along 70.5° line, which is approximately identical with cowl reflect shock at \( M_{	ext{a}} = 3.5 \). Its forebody leading edge radius is 0.5 mm and cowl leading edge radius is 0.25 mm.

Shape transition techniques are used from throat to isolator exit to generate a rectangle exit isolator. As shown in Fig. 3(b), the blue line indicates throat shape and the black line
is isolator exit shape. Area and geometrical center of the isolator are maintained constant along x-coordinate direction. The length of isolator is 0.21 m, about 9.7 times the height of throat. Width to height ratio at the isolator exit is 4.2.

3. Experimental setup

Wind tunnel experiments are conducted at China Aerodynamic Research and Development Center’s (CARDC) 0.6 m Straight Intermittent Trisonic Wind Tunnel (SITWT). SITWT has a 0.6 m × 0.6 m test section with the operation Mach number ranging from 0.4 to 4.5. Under supersonic conditions, its test section’s length is 1.575 m. The experimental model is tested at \( M_{\infty} = 4.03 \), 3.53 and 3.01. Table 1 is the wind tunnel’s operation conditions. \( P_t \) is total pressure, \( T_0 \) is total temperature and \( Re \) is Reynolds number of incoming flow.

![Image](https://example.com/image1)

**Fig. 3** Three dimensional view of the experimental model and its isolator.

<table>
<thead>
<tr>
<th>( M_{\infty} )</th>
<th>( P_t ) (MPa)</th>
<th>( T_0 ) (K)</th>
<th>( Re ) (m(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.03</td>
<td>0.63</td>
<td>288</td>
<td>( 3.09 \times 10^7 )</td>
</tr>
<tr>
<td>3.53</td>
<td>0.54</td>
<td>288</td>
<td>( 3.37 \times 10^7 )</td>
</tr>
<tr>
<td>3.01</td>
<td>0.36</td>
<td>288</td>
<td>( 2.91 \times 10^7 )</td>
</tr>
</tbody>
</table>

Table 1 Wind tunnel test conditions.

Formulations accounting for the non-uniform pressure distributions in flow meter are used to calculate mass flow rate for the experimental model. They are shown below and flow in the flow meter is assumed to be throttled to subsonic conditions.
\[
\phi = \sum_{j=1}^{n} s_j P_j q(\lambda_j) / A_{0q} q(\lambda_0) P_{\infty, j}
\]

where

\[
q(\lambda_j) = \left( \frac{\gamma + 1}{2} \right)^{\gamma/2} \left( 1 - \frac{\gamma - 1}{\gamma + 1} \lambda_j \right) \lambda_j;
\]

\[
\lambda_j = \sqrt{\frac{\gamma + 1}{\gamma - 1} \left( 1 - (P_j / P_0)^{\gamma} \right)}
\]

\(q(\lambda_j)\) is mass flux ratio. In the present formulations, the number of pitot probes is 16 \((n = 16)\), and \(A_0\) is the captured area. \(P_j\) and \(P_0\) are static pressure and pitot pressure respectively. \(s_j\) is the corresponding control area governed by pitot/static pressure probe \(j\), and the cumulated sum of \(s_j\) equals to flow meter’s cross section area. \(P_{\infty, j}\) is total pressure of incoming flow. \(\gamma\) is heat specific ratio of air. \(\lambda_j\) and \(q(\lambda_j)\) are flux functions of Eq. (2).

Fig. 7 is schlieren maps of the experimental model at \(Ma_{\infty} = 4.0\) and 3.5 at different AOAs during the measuring procedures of mass flow rates. The throttling positions are \(x_c = 90\) mm for \(Ma_{\infty} = 4.0\) and \(x_c = 89\) mm for \(Ma_{\infty} = 3.5\), which will keep the flow in the mass flow meter fully throttled, but at the same time, the inlet is still fully started. \(x_c\) is the throttling cone position.

Fig. 8(a) is the measured mass flow rate at different throttling cone positions corresponding to different incoming flow conditions. Except non-fully throttled and unstart conditions, the measured values for each condition at different throttling cone positions are identical. Mean squared errors of the measured data corresponding to each free stream condition are less than 2%. Fig. 8(b) presents the measured mass flow rates at different free stream Mach numbers and angles of attack. From those results, when the OICWI is fully started, its mass flow rate is probably proportional to the angle of attack. Mass flow rate is quite low at \(Ma_{\infty} = 3.0\) because of the unstart inlet.

4.2. OICWI’s anti-backpressure ability

Fig. 9 shows mean static pressure distribution on body side’s symmetric plane when the throttling cone moves forward and back. When the throttling cone moves forward from 85 mm to 100 mm, mean static pressure in isolator increases gradually until \(x_c = 95\) mm. At \(x_c = 100\) mm, pressure rise has moved forward to the forebody areas and the inlet is unstarted. Comparing Fig. 9(a) with (b), we can see that beginning position of pressure rise at body side is slightly ahead of that at cowl side at the same throttling cone position. This means that flow boundary layer of body side is thicker than that of cowl side. This phenomenon causes flow separation and it makes back pressure move forward more easily on body side than on cowl side. When the throttling cone moves forward and then moves backward to the same position, such as at \(x_c = 95\) mm and \(x_c = 85\) mm, pressure distributions on
symmetric plane are almost identical with each other. This means that flow delay phenomena during the inlet’s restart process in present experimental conditions are weak. $P$ is static pressure on static pressure taps of the experimental model.

Fig. 10 presents the filtered dynamic pressure distribution on D3 and D13 at $Ma_{\infty} = 4.0$ and AOA = $0^\circ$ during the inlet’s unstart process. Keeping on moving throttling cone forward beyond $x_c = 98$ mm, back pressure at D13 will rise until buzz occurs and inlet is unstarted. The maximum back pressure is obtained by using mean static pressure at D13 just before buzz occurs. Table 2 is the maximum anti-backpressure at different $Ma_{\infty}$ and AOAs. The maximum anti-backpressure increases with increasing $Ma_{\infty}$ and AOA. Their values are about 40 and 26 times $P_1$ for $Ma_{\infty} = 4.0$.
and 3.5 respectively. \( P_d \) is the dynamic pressure value on dynamic pressure sensors D3 and D13. \( P_{\text{bmax}} \) is the maximum anti-back pressure of the experimental model.

### 4.3. OICWI’s start and restart ability

Fig. 11(a) presents the start, unstart and restart schlieren maps of the OICWI at \( M_{\infty} = 4 \) and \( \text{AOA} = 0^\circ \). The inlet is fully started as wind tunnel sets up. When the throttling cone moves forward to 100 mm, back pressure increases and the inlet is fully unstarted. When the throttling cone moves back to 92 mm, the inlet is restarted again. Fig. 11(b) shows the dynamic pressure distribution on D3 and D13 during the inlet’s restart process. During the inlet’s unstart process, the inlet’s flow field is buzzing and the dynamic pressure on D3 and D13 has high-amplitude and low-frequency vibrations. As the throttle cone moves backward, buzz vanishes and shock train is swallowed into the isolator. Back pressure is still high during this period, and the low-amplitude but high-frequency vibration signals appear on D13.

Fig. 12(a) presents the start, unstart and restart schlieren maps at \( M_{\infty} = 3.5 \) and \( \text{AOA} = 0^\circ \). Fig. 12(b) shows dynamic pressure distribution during the inlet restart period. Phenomenon and conclusions are similar with the above case. The difference is that when the throttling cone comes to \( x_c = 95 \) mm, the inlet has already been fully unstarted. This

### Table 2 Maximum anti-backpressure at different \( M_{\infty} \) and AOAs.

<table>
<thead>
<tr>
<th>( M_{\infty} )</th>
<th>( \text{AOA} (^\circ) )</th>
<th>( P_{\text{bmax}}/P_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.03</td>
<td>0</td>
<td>38.5</td>
</tr>
<tr>
<td>4.03</td>
<td>4</td>
<td>41.1</td>
</tr>
<tr>
<td>3.01</td>
<td>0</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Fig. 10 Filtered dynamic pressure distribution at D3 and D13 at \( M_{\infty} = 4.0 \) and \( \text{AOA} = 0^\circ \) during inlet’s unstart period.

Fig. 11 Restart phenomenon at \( M_{\infty} = 4.0 \) and \( \text{AOA} = 0^\circ \).

Fig. 12 Restart phenomenon at \( M_{\infty} = 3.5 \) and \( \text{AOA} = 0^\circ \).

Fig. 13 Unstart phenomenon at \( M_{\infty} = 3.0 \) and \( \text{AOA} = -4^\circ, 0^\circ \) and \( 4^\circ \).

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phenomenon shows that the inlet can only withstand a lower maximum back pressure at $M_{\infty} = 3.5$ than that at $M_{\infty} = 4.0$. As the throttling cone keeps moving backward, the inlet is fully restarted. The low-amplitude and high-frequency static pressure vibrations on D13 vanish as the back pressure keeps on decreasing.

Fig. 13(a) shows that the OICWI cannot fully establish start flow patterns from AOA = $-4^\circ$ to AOA = $4^\circ$ at $M_{\infty} = 3.0$. There are strong separation shocks at body side in front of cowl lip. Reflected oblique shocks on cowl side are still visible. This means that flow field is supersonic at cowl side and flow separation occurs mainly at the body side. Fig. 13(b) presents the dynamic pressure signal on D3 and D13 at AOA = $0^\circ$. Pressure vibrations can be seen obviously. Vibrations on D3 are stronger than those on D13 since flow separation occurs mainly at the entrance of the inlet’s inner compression part.

5. Conclusions

The design method of osculating inward turning cone waverider forebody inlet has been introduced in this paper. The waverider forebody and inlet are integrally designed with no artificial modifications of their compression surface. An OICWI experimental model is designed under geometrical constraints. Wind tunnel experiments are conducted to test the performance of the designed OICWI from $M_{\infty} = 3.0$ to 4.0. The OICWI’s mass flow capture ratio is relatively high and it is 0.73 at $M_{\infty} = 4.0$ and AOA = $0^\circ$. The forebody inlet’s maximum anti-backpressure values are around 40 times $P_{\infty}$ at $M_{\infty} = 4.0$ and about 26 times $P_{\infty}$ at $M_{\infty} = 3.5$ (AOA = $0^\circ$). The OICWI can start and restart at $M_{\infty} = 3.5$ and 4.0 but cannot fully start at $M_{\infty} = 3.0$. The promotional results obtained from the present studies suggest that OICWI will be a good option for airbreathing hypersonic vehicle’s forebody inlet compression system. Present novel approach will promote the use of OICWI in the studies on hypersonic airbreathing vehicles and it is an important way to improve the propulsion to drag performance of hypersonic airbreathing vehicles.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cja.2016.09.007.

References

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