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Experimental investigation of a hypersonic I-shaped configuration with a waverider compression surface

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Lift-to-drag ratio (*L*/*D*) is nearly the most important index in determining the aerodynamic performance of a hypersonic flight vehicle, because the flight distance is linearly proportional to the *L*/*D* according to Breguet's equation. In general, the higher the *L*/*D* of a vehicle, the greater the flight range if the specific impulse, structural mass ratio, and flight velocity are given. Naturally, the pursuit of a high *L*/*D* for hypersonic vehicles has never ceased [1,2].

However, it is difficult to obtain a high *L*/*D* for hypersonic vehicles due to the presence of strong shock wave and massive viscous effects. As is well known, the *L*/*D* typically decreases with an increase in the flight Mach number in hypersonic regimes. A common empirical formula for introducing the relationship between the maximal *L*/*D* value and the flight Mach number has been provided by Küchemann [3] as follows:

$$(L/D)_{\max}=\frac{4(M_\infty+3)}{M_\infty}, \quad (1)$$

where $(L/D)_{\max}$ denotes the maximum *L*/*D*. The formula was obtained on the basis of various actual fight test and wind tunnel experimental data and termed "the lift-to-drag barrier" which has been widely accepted by the academic community.

The most effective means of improving hypersonic vehicle aerodynamic performance is through the use of the inherent characteristics of the hypersonic flow field [4]. A typical approach is the so-called waverider. The compression surface of such a configuration derives from a given flow field to ensure an attached shock wave at the sharp leading edge. At the designed Mach number and angle of attack, there is no flow spillage from the lower to upper surface; thus, it has the potential for a high *L*/*D*.

During the past few decades, various design and optimization investigations of the waverider have been carried out to pursue a high *L*/*D* [5]. Bowcutt et al. [6] developed a series of viscous optimized cone-derived waveriders using a numerical method that included the viscous drag within the optimization process. Bauer et al. [7] carried out an experimental investigation of two cone-derived waveriders that were designed using an optimization procedure considering both pressure and viscous drag. Miller et al. [8] carried out a similar study on osculating-cones-derived waveriders. The results showed that the maximum *L*/*D* is the highest among the vehicles that have been experimentally investigated under a similar condition (Mach 6), according to the existing published literature.

Based on the concept of high-pressure capturing wings (HCW) [9], a family of hypersonic I-shaped aerodynamic configurations (HIAC) has been proposed by taking advantage of the favorable utilization of the hypersonic flow field [10]. The HCW was first proposed by Cui et al. [10] With the aim of enhancing the aerodynamic performance of

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hypersonic vehicles with large volume requirements. The HCW is designed on top of the upwarp airframe and can produce a secondary shock wave after the body compression shock wave; thus, the high pressure acts on the lower surface of the HCW. Therefore, the lift of the vehicle can be considerably improved with a slight increase in the drag such that the L/D can significantly increase. Based on the concept of the HCW, hypersonic I-shaped configurations were proposed [10]. The numerical results show that a high L/D, volumetric efficiency, and lift coefficient can be simultaneously obtained.

The most representative feature of a HIAC is that there are two lifting surfaces on the upper and lower side of the body. Previous work mainly focused on the optimization of the upper lifting surface. Regarding the lower surface, a common flat compression surface has been adopted without detailed study. To further enhance the L/D, an optimized HIAC model in which the lower surface is designed as a waverider surface is proposed in this study.

According to this concept, the advantages of both waveriders and HCWs are fully retained because there is no coupled interference between the lower and upper lifting surfaces. Moreover, the high pressure generated by the lower surface can be completely enveloped. Simultaneously, the HCW can capture the high pressure generated by the upper surface. Therefore, the aerodynamic performance of the new configuration should be higher than that previously obtained.

To validate this idea, a conceptual configuration is designed and optimized. Furthermore, a wind tunnel experiment using a scaled model is carried out to test the configuration aerodynamic performance. The experimental model is shown in Figure 1(a). The model has a total length of 500 mm, width of approximately 312 mm, and height of approximately 129 mm. The volume and planform area of the model are 0.00192 m^3 and 0.0995 m^2, respectively. Therefore, the volumetric efficiency of the model is approximately 0.155.

The experiment was conducted in the Φ1m hypersonic wind tunnel (FD-30) in the China Aerodynamic Research and Development Center. The facility is an intermittent blow-down wind tunnel that has a wide simulation range and the ability to conduct a large-scale model simulation. The Mach number range is from 3 to 10 and the Reynolds range is from 1.5×10^5 m^{-1} to 5.9×10^7 m^{-1}. The total temperature is less than 1100 K and the total pressure is less than 12 MPa. The effective experimental time can extend beyond 30 s.

The experiment was conducted at freestream Mach numbers 5 and 6. The respective values of the freestream parameters are listed in Table 1, where Ma is the Mach number; P_0 is the total pressure; T_0 is the total temperature; Re is the Reynolds number; and P_∞ and T_∞ are the static pressure and temperature, respectively. The range of the angles of attack is from −2° to 8° during the two experiments.

The experimental results show that the $(L/D)_{max}$ occurs at

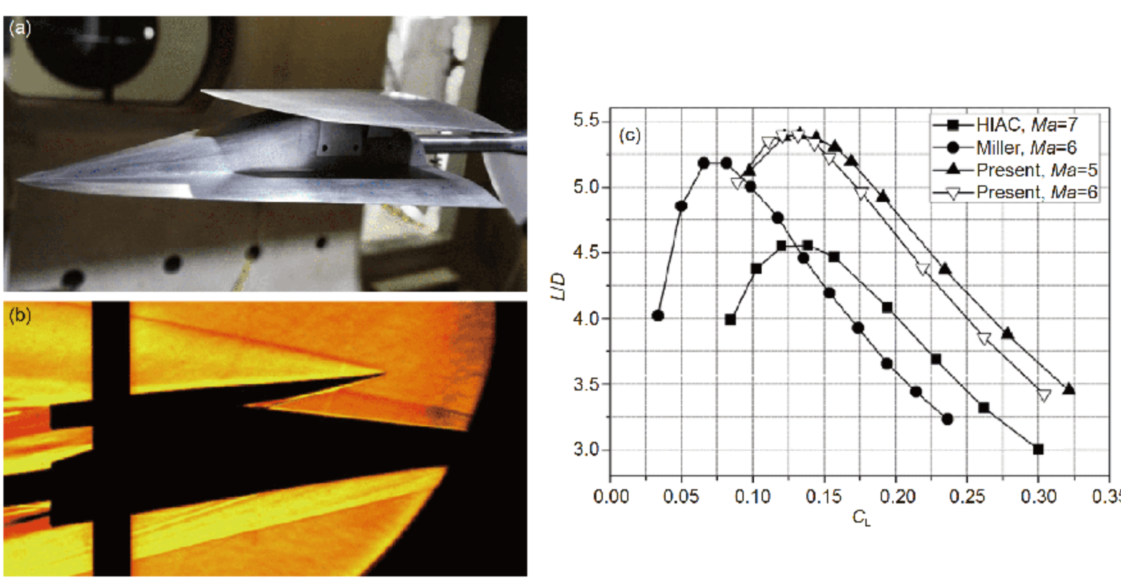

Figure 1 (Color online) Experimental model, schlieren photograph, and aerodynamic characteristics. (a) Experimental model, (b) schlieren photograph at Mach 6 $(L/D)_{max}$ condition, and (c) curves of L/D versus C_L.

Table 1 Experimental conditions

Ma	P_0 (Pa)	T_0 (K)	P_∞ (Pa)	T_∞ (K)	Re (m^{-1})
5	1.0×10^6	620	2.0×10^3	104	0.94×10^7
6	2.0×10^6	620	1.3×10^3	76	1.2×10^7

an approximate angle of attack of −0.5° at both Mach 5 and Mach 6. Figure 1(b) clearly shows the two shock waves generated by the HCW and the lower compression surface, and there is indeed no coupled interference between the two lifting surfaces.

The curves of the L/D versus lift coefficient C_L are shown in Figure 1(c) (labeled as "Present, Ma=5" and "Present, Ma=6," respectively). The experimental results of the models proposed in ref. [10] (labeled as "HIAC") and ref. [8] (labeled as "Miller") are also plotted for comparison. The model proposed by Miller is an osculating-cones-derived waverider designed using the optimization procedure at Mach 6. The experimental results show that $(L/D)_{max}$ is the highest among the vehicles that have been experimentally investigated under similar conditions. The aerodynamic coefficients are calculated by taking the planform area of the model as the referenced area. Note from the figure that the values of $(L/D)_{max}$ and their corresponding C_L at Mach 5 and Mach 6 are nearly the same as those of the present model. Compared to the HIAC model, $(L/D)_{max}$ of the present model increases approximately 19% benefiting from the lower surface which is designed as a waverider. In addition, $(L/D)_{max}$ at Mach 6 increases approximately 5% compared to that of the model proposed by Miller. C_L corresponds to the $(L/D)_{max}$ that increased by approximately 86%. Furthermore, the volumetric efficiency of the model proposed by Miller is approximately 0.141; however, that of the present model is 0.155, approximately 10% larger.

In summary, an optimized HIAC model whose lower surface is designed as a waverider surface is proposed in this study. Furthermore, a series of experimental investigations of the aerodynamic performance were carried out. The results show that the configuration not only has the characteristic of a high L/D but also has a high C_L and volumetric efficiency. In the present study, only the leading edges of the two lifting surfaces were taken as design variables in the optimization loop. We believe that the aerodynamic performance could be further improved if other design variables, such as the control parameters of the shape of the compression surfaces, were considered in a future optimization process.

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