An overview of research on wide-speed range waverider configuration

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Abstract: Hypersonic flight is becoming a common development goal of aeronautical and astronautical technology, thus mandating the requirement that hypersonic vehicle have good aerodynamic performance over a wide-speed range. Considering that a waverider is regarded as one of the most promising designs for air-breathing hypersonic vehicles, various design methods of the wide-speed-range hypersonic vehicle based on the design approach of waveriders have been proposed. This paper reviews and classifies wide-speed-range waverider design methodologies developed up until 2019, including the "combined" wide-speed range waverider, the variable Mach number waverider, the vortex lift waverider, the dual/multistage waverider, the morphing waverider, and some other wide-speed-range waverider designs. The current status of the waverider technology is summarized and future development ideas and trends are discussed.

Keywords: "Combined" wide-speed range waverider; variable Mach number waverider; vortex lift waverider; dual/multistage waverider; morphing waverider

1. Introduction

The aerodynamic design is a very basic and important part of any aircraft development process,

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because it directly affects the flight performance and flight quality of the entire aircraft, and it has a decisive impact on the flight safety, flight efficiency and economy. At the same time, the aerodynamic design results also directly affect the design of the aircraft structure and of the control system. Küchemann [1] presented a comprehensive review of the aerodynamic design of aircraft which included a chapter on the waverider. In fact, the waverider is a special class of the lifting body aerospace vehicles [2]. Its particularity is that it is a type of vehicle that uses its own shockwave attached to the leading edges to generate extra lift in a high-pressure area below the vehicle to improve its lift-to-drag ratio [3][4]. This characteristic makes it possible to break the 'L/D barrier' that Küchemann established, which is the great advantage of the special configuration of the waverider [5]. Rodi [6] employed Bezier Curve leading edges to reduce the peak leading edge laminar heating for three waverider-based hypersonic vehicles. At the design Mach number, the waverider "rides" on its shock wave attached to the waverider's leading edges, the flow between the shock wave and the waverider's compression-stream surface is fully contained, and there is no spillage from the compression-stream surface to the free-stream surface. This high pressure contained in the flow below the compression-stream surface allows the waverider to have superior aerodynamic performance advantages, such as higher lift-to-drag ratio than conventional, nonwaverider hypersonic configurations. However, at off-design Mach numbers, the shock wave is detached from the waverider's leading edges and there is flow spillage, which will adversely affect the aerodynamic performance advantages of the waverider. This is also one of the restraints on the practical application of the hypersonic waverider. That is to say, the optimal waverider configuration is highly dependent on Mach number, and a small deviation from the design point may significantly degrade its aerodynamic performance advantages over conventional vehicles [7][8].

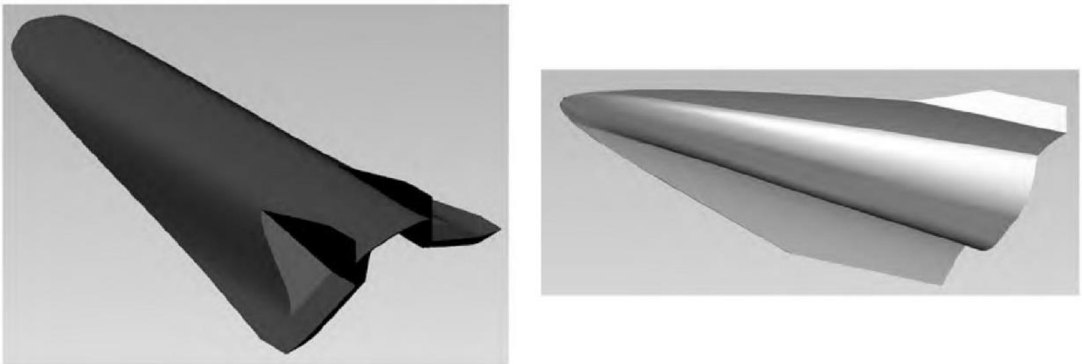
Therefore, many researchers [9][10][11][12][13][14] have attempted to make the waverider meet various practical needs, and after decades of development, the waverider configuration has developed into the waverider family of vehicles [15][16][17][18][19][20]. For example, in order to further increase the lift-to-drag ratio of waveriders at useful lift coefficients, the Osculating Cones Method was developed [21][22][23][24]. On this basis, the Osculating Flowfield Method was also proposed. This research showed that waveriders generated with the Osculating Flowfield Method have a higher lift-to-drag ratio than those created using the Osculating Cones Method [25][26][27][28][29][30][31]. In order to ensure that the lift-to-drag ratio and volumetric efficiency of a hypersonic airplane are both at a high level, Cui et al. [32] proposed a type of hypersonic airplane configuration with a double flanking air inlets layout, and Rodi [33] developed an optimization process for the Osculating Flowfield waverider generation method. In order to provide a highly uniform inlet flowfield to a scramjet engine system, the waverider was used as the forebody of the air-breathing hypersonic vehicle [34][35][36][37][38]. Furthermore, in order to take full advantage of the waverider's high lift-to-drag characteristics and the ideal pre-compression surface for the engine, the waverider design was used as the basis for the design of the entire air-breathing hypersonic vehicle [39][40][41][42][43]. At present, faced with the inevitable development target of developing a reusable Aerospace Vehicle (AV) for an Earth/Orbit Space Transportation System, the study of waveriders has also ushered in new development opportunities. Therefore, in order to overcome the technical limitation of the single Mach number waverider configuration, and also to better satisfy the practical requirement of the aerospace vehicle's wider speed range and wider airspace, a variety of novel designs have been proposed.

The main objective of this paper is to summarize the various current design methods for waveriders with a wide-speed range, and to discuss the next development ideas and trends of the wide-speed range waverider. The remainder of this survey is organized as follows. Sections 2-7 detail the several types of wide-speed range waverider designs. Section 8 provides a discussion and Section 9 concludes this paper.

2. The "combined" wide-speed range waverider

Just as its name implies, the "combined" wide-speed range waverider is a combination of the waverider generated under different design conditions by splicing either directly or by using the connecting segments. The expected goal of this scheme is to combine two or more waveriders generated under different design conditions to ensure that when the flight Mach number varies within a certain range, a part of the aerodynamic performance of the designed waverider decreases while the other part increases. Therefore, the overall aerodynamic performance of the designed waverider is better under wide-speed flight conditions.

In 2009, in order to improve the aerodynamic performance of the waverider in the full-speed range of the flight envelope, Wang et al. [44] put forward a wide-speed range waverider design method by means of combination and stitching. The design schemes are as follows: Firstly, they used the osculating cone theory to design a hypersonic waverider (Mach number Ma=6.0, flight height H=30km) and a low-speed waverider (Mach number Ma=3.0, flight height H=15km), and performed an engineering design according to relevant requirements, as shown in Fig. 1. And then, by joining the low-speed waverider and hypersonic waverider with an adapter, a wide-speed range waverider was designed, as shown in Fig. 2. The results of wind tunnel test and numerical simulation show that the maximum lift-to-drag ratio of this wide-speed range waverider is more than 3.5 over the entire flight envelope ($0.3 < Ma < 7.0$), which indicates that it can maintain a good aerodynamic performance in the wide-speed range of subsonic, transonic, supersonic and hypersonic speeds.



(a) The hypersonic waverider configuration (b) The low-speed waverider configuration

Fig. 1 The hypersonic and low-speed waverider configurations generated by the osculating cone theory [44].

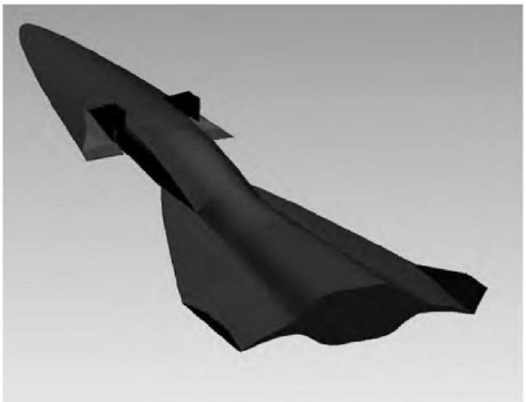
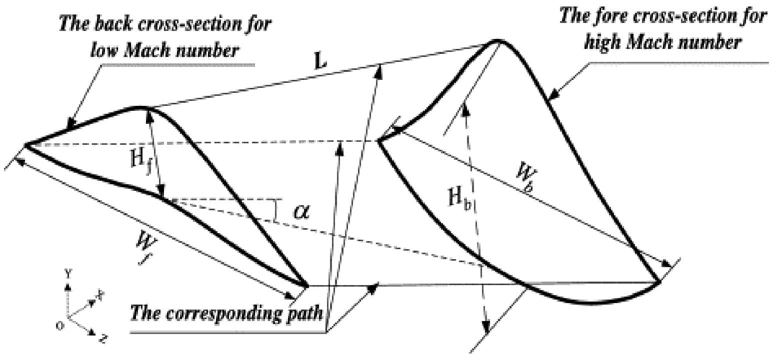
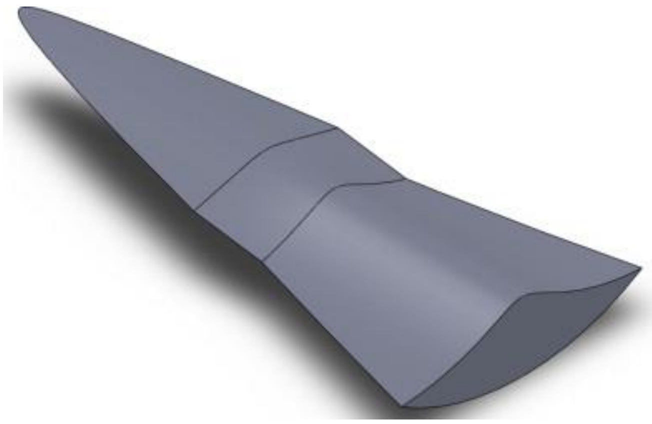


Fig. 2 The wide-speed range waverider configuration [44].

In 2013, in order to study the influence of the connection section on the aerodynamic performance of the "tandem" wide-speed range waverider, Li et al. [45] designed a "tandem" wide-speed range waverider based on the cone-derived theory, as shown in Fig. 3. The effects of the length of the connection section, the thickness of the front body and the width of the rear body on the aerodynamic performance of such a wide-speed range waverider were analyzed by means of the numerical approaches. The obtained results show that the lift-to-drag ratio of the "tandem" wide-speed range waverider is proportional to the length of its connection section, the thickness of its forebody and the width of its afterbody. The length of the connection section has the most obvious influence on the aerodynamic performance of such an aircraft, and the influence of the width of the afterbody on its overall aerodynamic performance is not obvious. In addition, the influence of the forebody's thickness and the connection section's length on the aerodynamic performance of the aircraft is coupled.



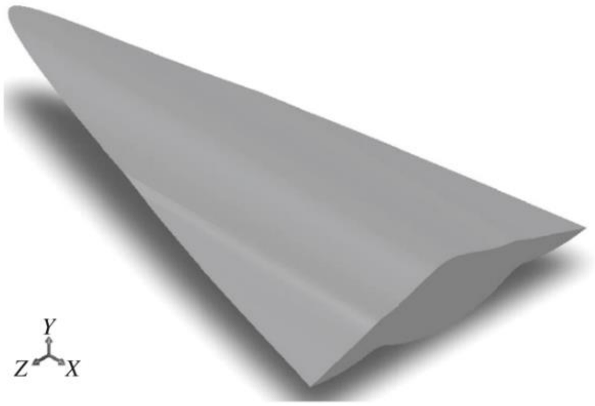
(a) Generating principle of the connection section



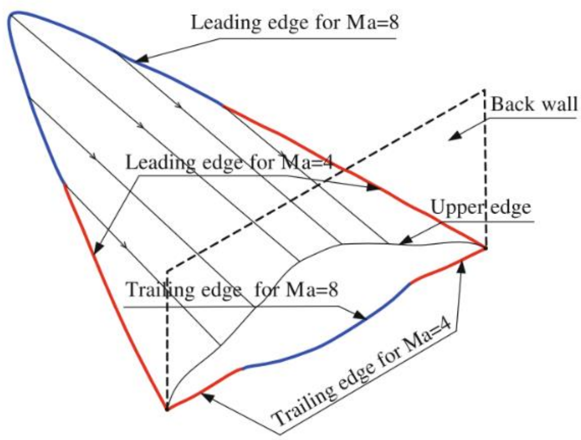
(b) The configuration of the "tandem" wide-speed range waverider

Fig. 3 The "tandem" wide-speed range waverider [45].

In 2014, inspired by the design method of the "tandem" wide-speed range waverider, and considering that the shock wave characteristics of the waverider are mainly determined by the shape of its leading-edges, Li et al. [46] also designed a "parallel" wide-speed range waverider, as shown in Fig. 4 (a). The idea of the design is to first obtain the leading-edges of the two benchmark models of the high-Mach and low-Mach waveriders by using the design theory of the cone-derived waverider. Then, the two leading-edges are combined in parallel to obtain the "parallel" wide-speed range waverider. The generation of its trailing edge is also the same, as shown in Fig. 4 (b). The numerical results show that compared with the two reference configurations, the "parallel" wide-speed range waverider has a higher lift-to-drag ratio in the hypersonic speed range, which shows that the “parallel” design method can improve the overall aerodynamic performance of the waverider. Moreover, the wide-speed range waverider designed in parallel mainly improves its lift-to-drag ratio by reducing its flight drag.



(a) The configuration of the "parallel" waverider



(b) The design theory of the “parallel” waverider

Fig. 4 The "parallel" wide-speed range waverider [46].

In addition to the above-mentioned design method of combining and splicing two waveriders, it is also possible to combine several waveriders, that is, a kind of design called the star-body waverider. Similar to the star-shaped body, they can be generated by combining a plurality of wedge-derived waveriders, conceived by Nonweiler [47], as shown in Fig. 5. Its advantage is that they have a lower wave drag than the right circular cones with equivalent length and volume [48][49][50].

However, because the star-body waverider shown in Fig. 5 is generated for the same design Mach number, the shock wave will no longer attach to the fin leading edges when flying at any Mach number other than the design Mach number, resulting in shock detachment, thus reducing aerodynamic efficiency, which is not conducive to the wide-speed flight of the waverider. In addition, because the wedge sections of the star-shaped body have the same flow deflection angle, such an axisymmetric configuration will only produce a finite aerodynamic drag while flying at zero angle of attack, but will not contribute to the lift or side force. In view of the above problems, Stephen Corda designed a class of star-body waveriders with multiple design Mach numbers by arranging different design Mach numbers for each center wedge section [51], as shown in Fig. 6. It may produce a more optimized aerodynamic configuration “tailoring” over a range of Mach numbers. On this basis, using the computational fluid dynamics method, Corda analyzed the aerodynamic characteristics of a single- and multiple-design-Mach-number star-body waverider. The numerical results show that the single-design-Mach number star-body waverider has higher skin-friction drag, lower wave drag, and lower total drag than the equivalent volume cone. Because the volume and the wetted surface areas of the multiple-design-Mach-number star-body waverider are relatively large, its total drag is higher than that of the equivalent cone, but for some of these new configurations with higher Mach numbers, their wave drag and drag coefficient are lower than that of the equivalent cone. Furthermore, in order to generate lift or side force, the section of the multiple-design-Mach-number star-body waverider should be designed as follows: the sector with the higher design Mach number should correspond to the desired direction of force.

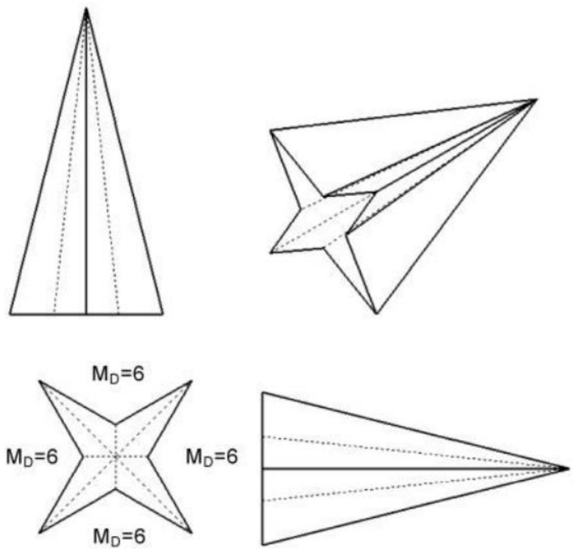


Fig. 5 The star-body waverider with one design Mach number, $Ma_D = 6.0$ [47].

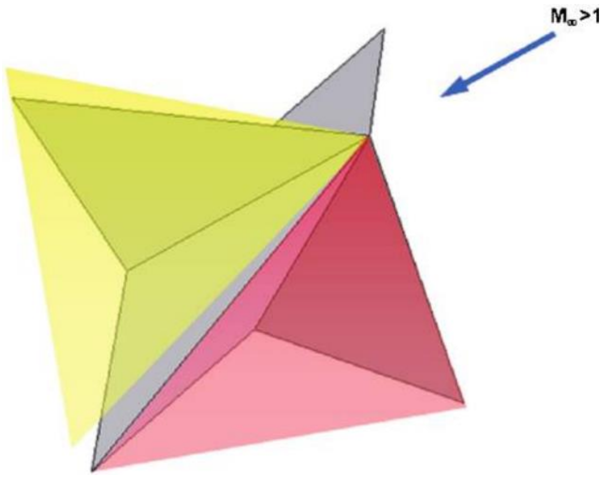


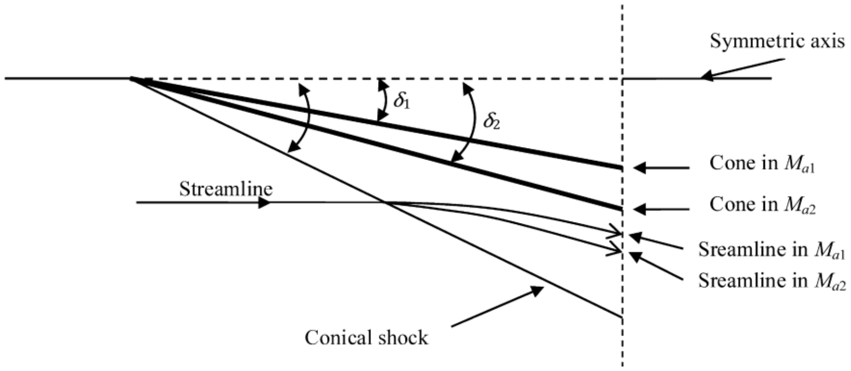
Fig. 6 The multiple-design-Mach-number star-body waverider [51].

Among the various design schemes for wide-speed range waveriders proposed at present, the design idea of combination and splicing is undoubtedly the most intuitive. It can be seen from the current research results that the aerodynamic performance of the wide-speed range waverider designed with this idea is superior to the ordinary waverider that constitutes it. However, this design idea is based only on artificially splicing the waverider simply and mechanically. Therefore, it is subject to the subjective influence of the designer, and there are the problems of high human participation and poor repeatability.

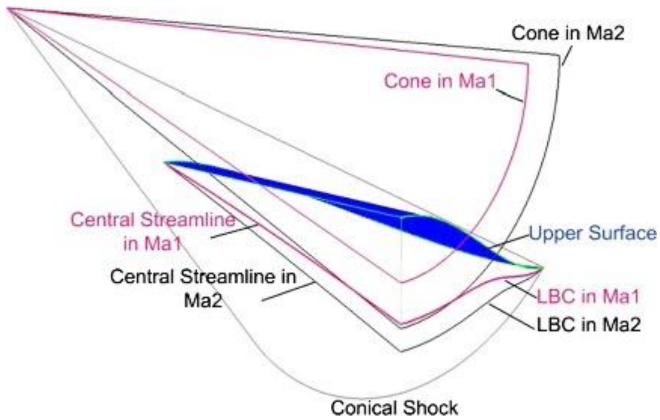
3. The variable Mach number waverider

The design method of the variable Mach number waverider is a kind of design method of waveriders with a wide-speed range, which can be combined with different osculating theories in the spanwise direction to obtain the corresponding design method of waveriders with a wide-speed range. The design idea is to design the waverider based on the basic flow field generated by multiple design Mach numbers, so as to achieve the goal of taking into account various flight states for wide-speed flight.

In 2017, based on the basic law of conical flow, Zhang et al. [52] first studied the nature of the conical flow field when the Mach number of the free-flow changed, and its effect on the geometry of the generated conical-derived waverider, as shown in Fig. 7. Then, a novel design approach for the wide-speed-range vehicle was proposed on the basis of the design theory of the cone-derived waverider, which is the design method of the conical-derived variable Mach number waverider. The basic design idea is to use a streamline-tracing technique to generate streamlines on the lower surface of the conical-derived variable Mach number waverider in different lateral areas, such that different design Mach numbers are allocated, and then the lower surface of the aircraft is obtained by the lofting method, as shown in Fig. 8.



(a) The conical flow field



(b) The configuration of the conical-derived waverider

Fig. 7 The effect of the variation of the free stream Mach number [52].

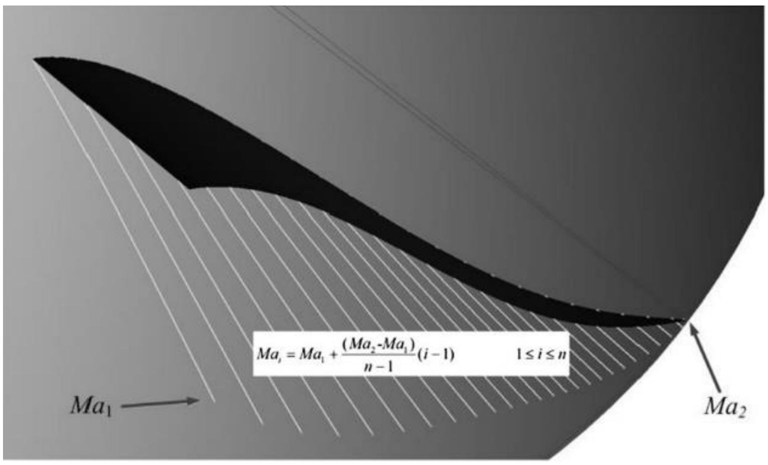


Fig. 8 The design schematic of the conical-derived variable Mach number waverider [52].

The numerical simulation results show that the designed conical-derived variable Mach number waverider has better wave-ride properties in the design Mach number range due to the compromised aerodynamic performance compared with the waveriders generated under two ultimate design Mach numbers. In addition, the conical-derived variable Mach number waverider whose design Mach number decreases from the edge to the vehicle's symmetry plane continuously has better aerodynamic performance than the one whose design Mach number increases from the edge to the vehicle's symmetry plane.

Subsequently, using similar design ideas, Li et al. [53] also carried out the design of the variable Mach number waverider. The design steps of the conical-derived variable Mach number waverider are given in detail, as shown in Fig. 9. The study results indicated that the overall performance of the variable Mach number waverider is superior in the wide-speed range. The variation of the design Mach number has a great influence on the aerodynamic performance of the waverider, confirming the conclusion in Ref. [52]; furthermore, when the thickness of the waverider is kept the same, the variable Mach number waverider has a stronger shock wave compression ability than the ordinary waverider.

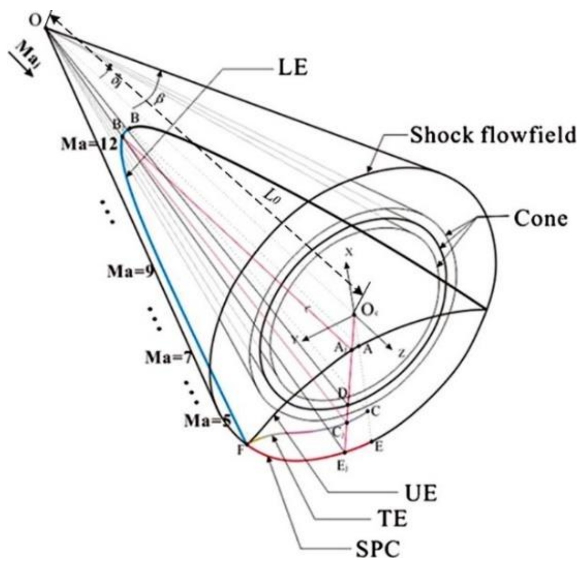


Fig. 9 Schematic diagram of the variable Mach number waverider generation approach [53].

To further expand the application range of the variable Mach number waverider design method, a novel design method for the wide-speed range waverider, which combines the design method of the variable Mach number waverider with the osculating cone theory, was proposed by Zhao et al. [54] in 2018. The design idea is to configure conical flow fields with different free stream Mach numbers for each osculating plane to obtain the three-dimensional supersonic flow field required for the design of the osculating cone variable Mach number waverider, as shown in Fig. 10. The numerical simulation results show that over the whole flight profile, the osculating cone variable Mach number waverider has a higher lift-to-drag ratio than the conventional osculating cone waverider with the same volumetric efficiency, which reflects its aerodynamic performance advantages.

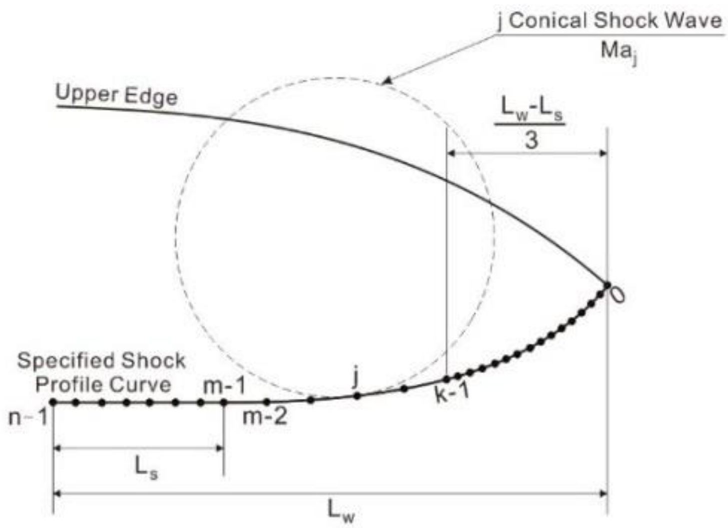


Fig. 10 The schematic diagram of the osculating cone variable Mach number waverider [54].

Based on the osculating flowfield method for waveriders, a design method for the variable Mach number waverider was developed by Liu et al. [55] in 2019. The definition of design parameters for the osculating flowfield waverider used in Liu’s waverider design is shown in Fig. 11. Their study results indicated that there is no obvious overflow phenomenon in the design Mach number range of the variable Mach number osculating flowfield waverider, which indicates that the aircraft has good waverider properties in the wide- speed range; furthermore, the leading edges of the variable Mach number osculating flowfield waverider are the same as those of the ordinary osculating cone waverider, but the trailing edges of its compression surface are different, as shown in Fig. 12. In addition, the variable Mach number osculating flowfield waverider also has a good balance between its main performance, namely aerodynamic performance and volumetric efficiency, thus indicating that the aircraft is more suitable for wide-speed range flight.

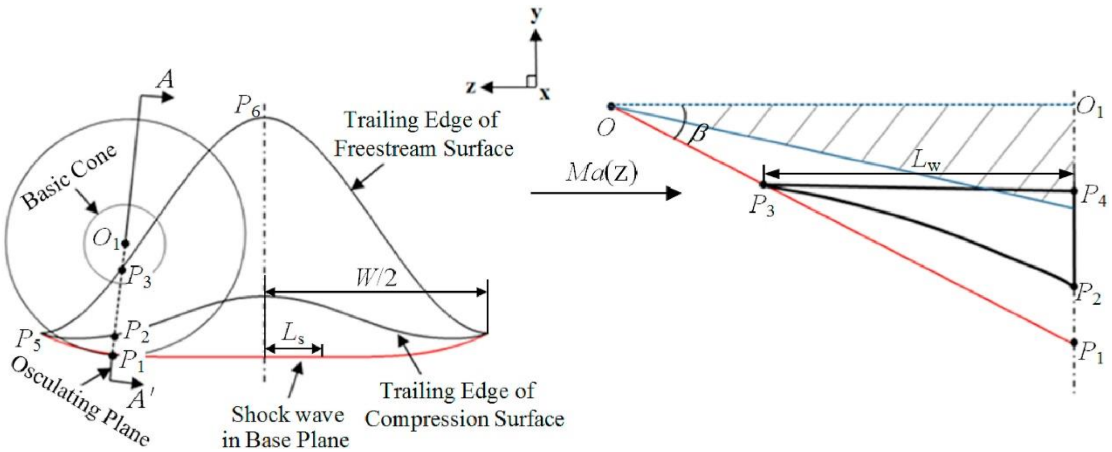


Fig. 11 The design parameters of the osculating flowfield waverider [55].

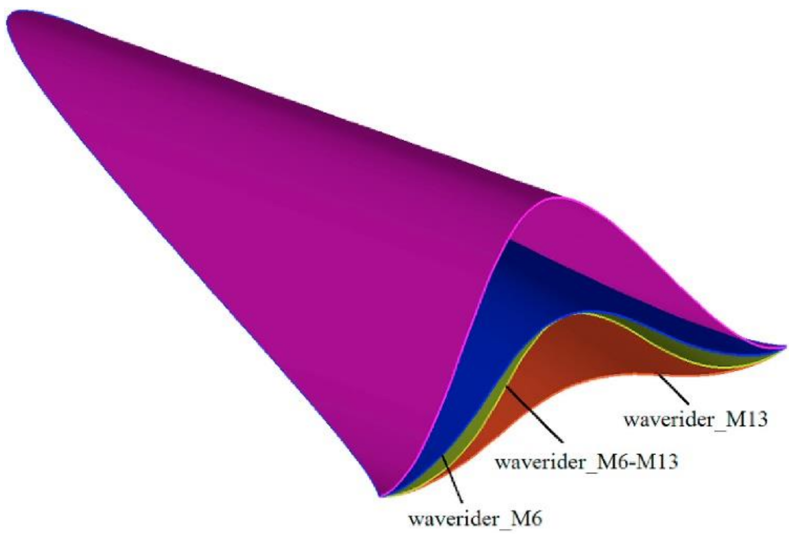


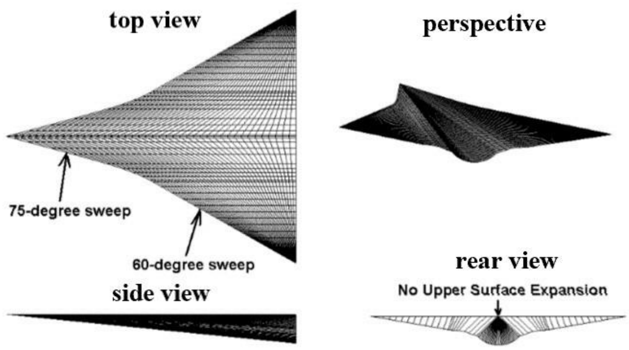
Fig. 12 Configuration comparison of the variable Mach number osculating flowfield waverider and ordinary osculating cone waverider [55].

Generally speaking, the design procedure for a waverider mainly includes the following three parts: designing and solving the basic flow field, tracing a group of streamlines in the basic flow field, and lofting all the streamlines to generate the upper surface and the compression-stream surface of the vehicle [56]. From this perspective, the design method of the variable Mach number waverider is to improve the wide-speed range characteristics of the waverider by changing the basic flow field. In fact, the original idea of this design method came from Ref. [46]. The first step to generate the "parallel" wide-speed range waverider configuration is to obtain the leading-edges of waveriders for the low and high design Mach numbers. Then, the leading edge of the wide-speed range vehicle is generated by combining the two leading edges in parallel. Secondly, the upper-edge on the back wall for the wide-speed range vehicle is generated according to the corresponding requirements. In the end, lofting all relevant streamlines forms the compression surface. The leading edge and upper-edge on the back wall form the freestream surface, and the upper-edge on the back wall and trailing edge of compression surface form the bottom surface. The trailing edge of the compression surface is obtained by tracking the leading edge to the back wall in the free stream direction. At this point, the design of the "parallel" wide-speed range waverider configuration is complete. Obviously, the second step is not only the key point of the design process, but also the main disadvantage of this design method, that is, there are problems of high human participation and poor repeatability. Therefore, in order to avoid manual splicing, the design method of the variable Mach number waverider is evolved by integrating this parallel design idea into the waverider design method.

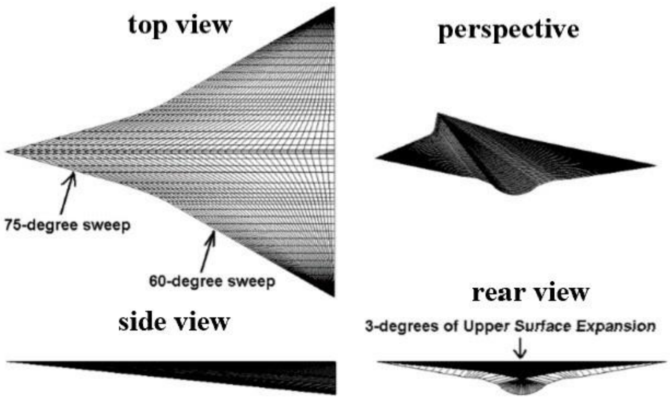
4. The vortex lift waverider

It is well known that the non-linear behavior of lift with angle of attack is known as vortex lift, which typically occurs on thin, highly swept, sharp-edged wings used for transonic and supersonic flight [57][58]. In addition, compared with the research efforts on high-speed vortex flows, a primary focus of the low-speed research has been on the use of vortex flows to improve aerodynamic performance [59]. Therefore, the rational use of vortex lift or low-speed vortex flows to design a waverider can be regarded as a method to improve its wide-speed-range characteristics, consistent with the original intention of the vortex lift waverider.

In 2005 and 2012, Rodi [25][60] first proposed the concept of the vortex lift waverider and described it as a new type of waveriders which can increase the lift of the vehicle by reducing the pressure on the leeward surface via designing for leading edge vortices. The vortex lift waverider with sweep angle schedules designed to produce strong leading edge vortices can be generated by utilizing the osculating flowfield waverider generation method and defined geometrical relationships to generate specific leading edge sweep angles [61]. In addition, in order to gain the "separation bubble with shock" flow domain that can generate the high lift producing vortices, Rodi [60] proposed two methods. Among them, the first method is to raise the waverider's angle of attack, and the second method is to include expansion on the leeward side of the waverider. Since the second approach reduces the volume of the vehicle, it is expected to be less desirable. An example using each method is shown in Fig. 13.



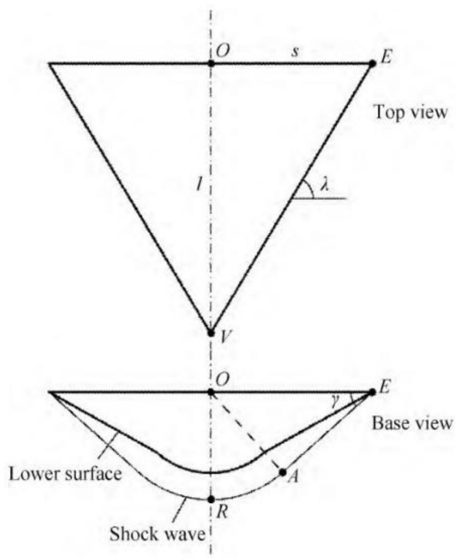
(a) The waverider generated by the first method



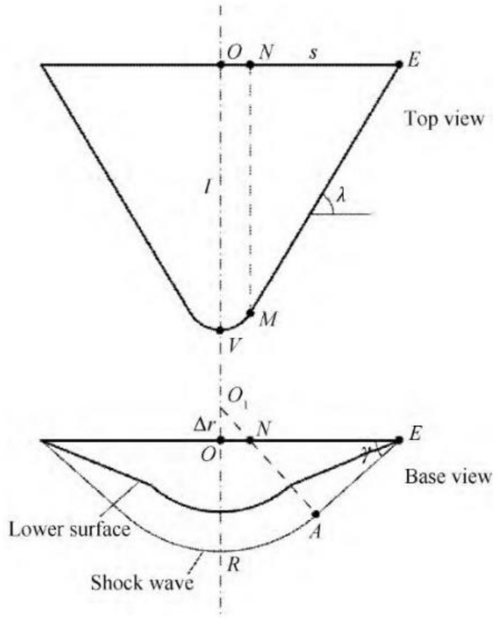
(b) The waverider generated by the second method

Fig. 13 The vortex lift waverider with a design Mach number of 6.0 [60].

The research in Ref. [60] focuses on the geometric characteristics and on the vortex lift characteristics of the vortex lift waverider, but the specific method of generating such an aircraft is not explained. Duan et al. [62] proposed in a detailed method of generating the waverider with constant angle of sweepback according to the osculating cone theory and the geometric characteristics of the vortex lift waverider. The design principle of the osculating cone waverider with constant angle of sweepback is shown in Fig. 14. Its waverider properties and vortex lift characteristics are verified by computational fluid dynamics (CFD) simulation.



(a) Geometry characteristic of the OCWRCAS I



b) Geometry characteristic of the OCWRCAS II

Fig. 14 Schematic illustration of generation method of the osculating cone waverider with constant angle of sweepback [62].

In 2017, according to the design method for the osculating cone waverider, Liu et al. [63] put forward the concept of the double swept waverider and gave the relationships between design parameters and configuration parameters. Fig. 15 illustrates the design schematic of the double swept waverider. Furthermore, using the non-uniform rational B-spline (NURBS) method to aid in generating the waverider, the design method to create the waverider with controllable configuration parameters (including the blunt head area, the sweep angle and the swept area) was studied. The results showed that the double swept waverider with an appropriate shape can improve its subsonic characteristics, aerodynamic stability and nonlinear vortex lift while maintaining the high hypersonic performance, thus providing a novel way to design the wide-speed range hypersonic vehicles.

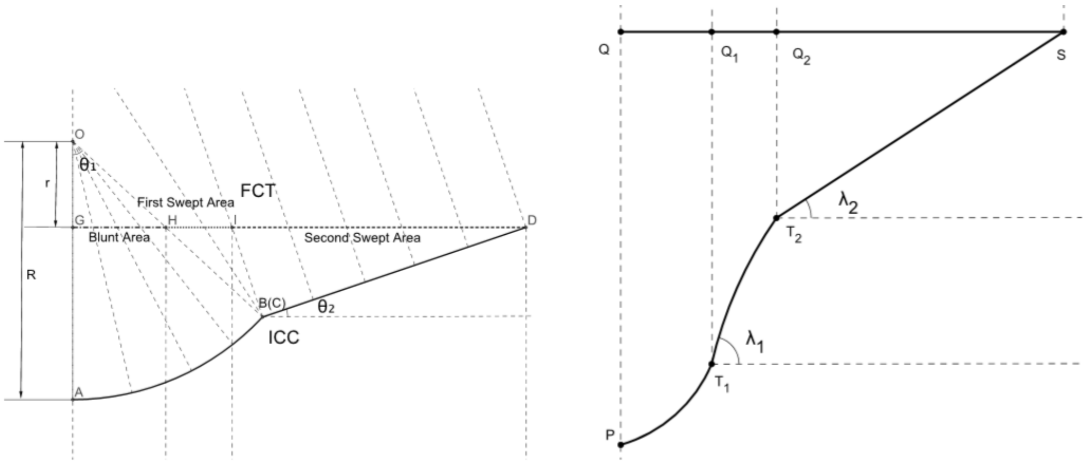
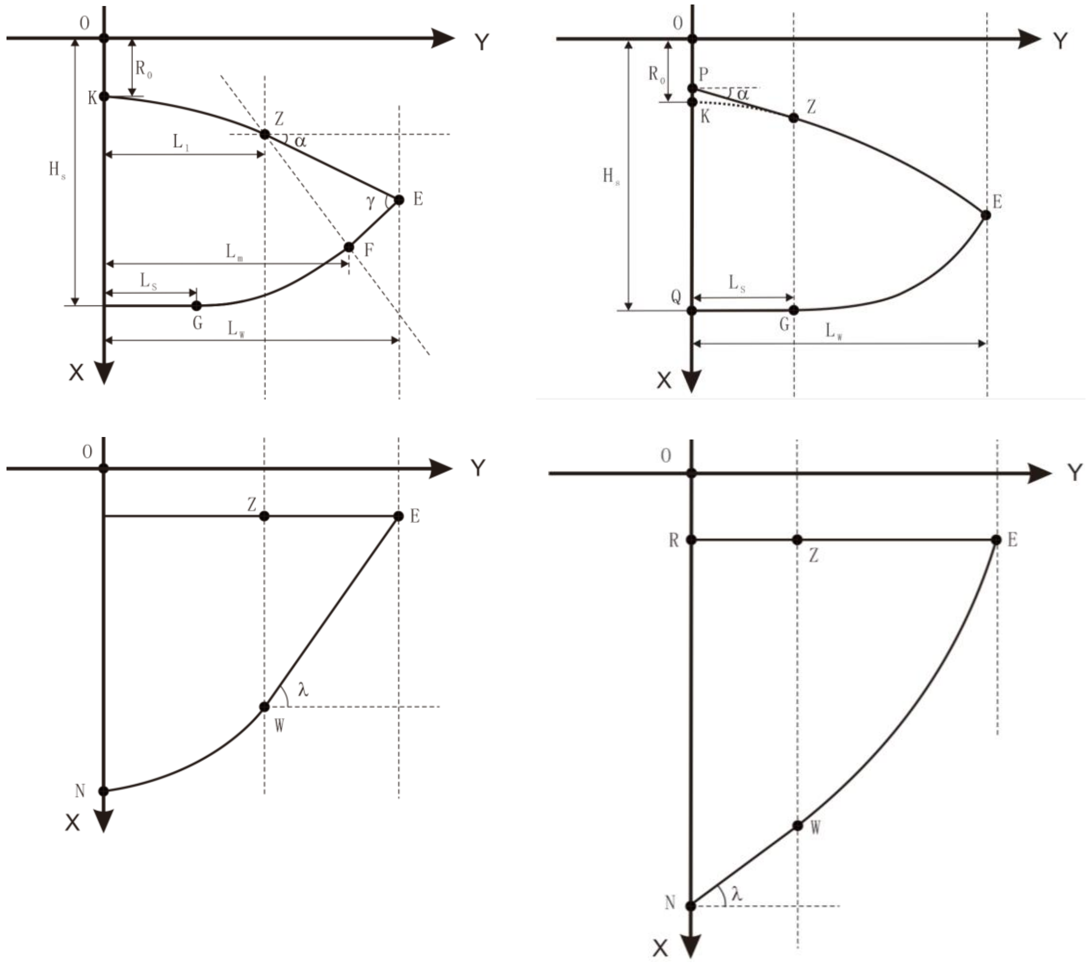


Fig. 15 Schematic representation of generation method of the double swept waverider [63].

In the above two methods of generating the constant swept waverider, the curved portion constituting the inlet capture curve (ICC) uses a circular arc, and the flow capture tube (FCT) is designated as a straight line, which severely limits the design space of the vortex lift waverider. Therefore, according to the geometrical relationship of the osculating cone waverider, Zhao et al. [64] presented design methods for two kinds of constant swept waveriders with more flexible design curves (ICC and FCT). They named them the cuspidal waverider and the delta-winged waverider, respectively. Their principles are illustrated in Fig. 16. Zhao et al. [64] designed a conventional osculating cone waverider which has the same volumetric efficiency as the delta-winged waverider and the cuspidal waverider, and they analyzed the performance differences between them. The comparison results showed that the aerodynamic performance of the cuspidal waverider is better than that of the general osculating cone waverider under any flight conditions in the high speed range, while the high speed aerodynamic performance of the delta-winged waverider is worse; the results also demonstrated that the lift coefficient curve of the cuspidal waverider exhibits a significant nonlinear increase in the high speed range, while the lift coefficient curves of the delta-winged waverider and the general osculating cone waverider do not have this property. This indicates that the different positions of the straight line segment in the leading edge of the waverider has different effects on the high speed aerodynamic performance of the waverider.

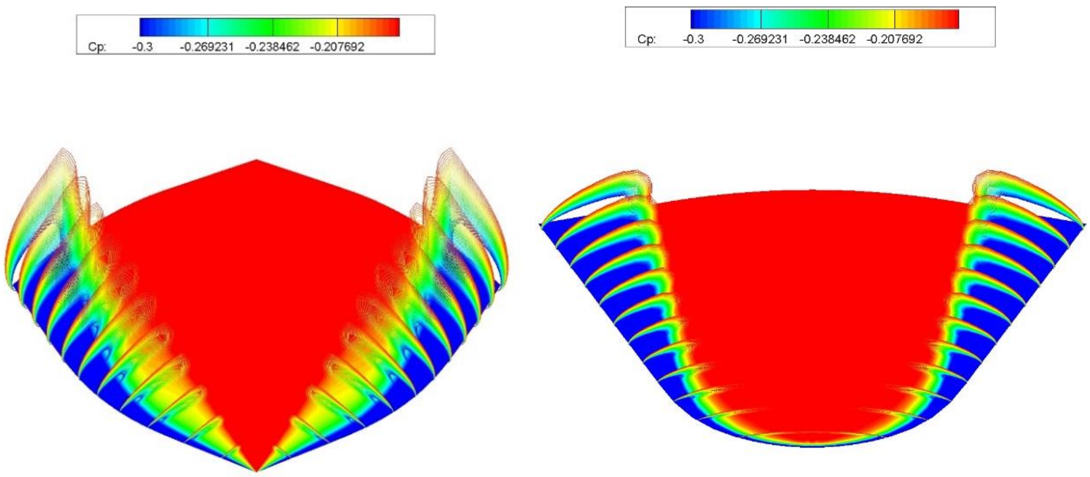


(a) Design geometry of the delta-winged waverider

(b) Design geometry of the cuspidal waverider

Fig. 16 Sketch for the design of the delta-winged waverider and the cuspidal waverider [64].

In addition, in order to further explore the low speed performance advantages of the two types of vortex lift waverider with a wide-speed range designed in Ref. [64], Zhao et al. [65] used the CFD approach to analyze the low speed viscous flow fields, the vortex lift characteristics, and the low speed viscous aerodynamic performances of the cuspidal waverider, delta-winged waverider and general osculating cone waverider. The analysis results indicated that the low speed lift-to-drag ratio of the cuspidal waverider is higher than that of the general osculating cone waverider with the same volumetric efficiency, while the low speed lift-to-drag ratio of the delta-winged waverider is lower. Moreover, the cuspidal waverider better balances the low-speed takeoff performance and the high speed cruise performance, further enlarging its own flight speed range, while the low-speed takeoff performance of the delta-winged waverider is poor, which is mainly caused by the differences in the low speed vortex structure of the three types of aircraft. Fig. 17 shows the low speed vortex structure of the cuspidal waverider and the delta-winged waverider under the flight condition.

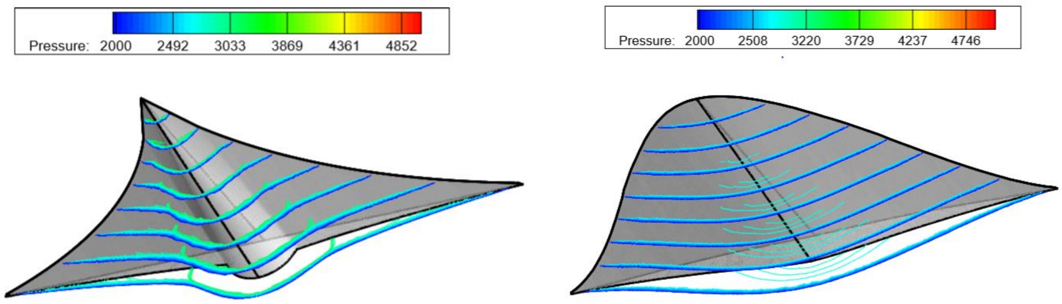


(a) The cuspidal waverider (b) The delta-winged waverider

Fig. 17 The low speed vortex structure of the cuspidal waverider and the delta-winged waverider [65].

On the other hand, considering that the shape of the aircraft, especially the planar shape, has a great influence on the aerodynamic and maneuvering characteristics of the aircraft, Liu et al. [66][67] developed the concept of the double swept waverider proposed in Ref. [63] and put forward the concept of the planform-customized waverider. Its design is based on a set of differential equations derived from the global geometric relationships among the inlet capture curve (ICC), flow capture curve (FCC) and planar shape curve (PSC) in the osculating-cone waverider design. This waverider design method can be used in the design of the wide-speed range waverider. The main idea is to introduce the vortex effect by customizing the planform for the waverider, thereby employing the vortex effect to improve the low speed aerodynamic performance and the shock effect to improve the super/hypersonic aerodynamic performance, respectively. The double swept waverider can be used to verify the correctness of this design concept. They then performed a comparison study of the double swept waverider and flat plate model using computational fluid dynamics (CFD) simulation. The study results showed that the aerodynamic performances of the waverider with reasonable planform is favorable under both subsonic and hypersonic conditions, remedying some deficiencies of the traditional waverider.

On this basis, Wang et al. [68] studied the design method for the waverider with a controllable planar shape as a new waverider design method, i.e., the design of the waverider is carried out by solving the differential equation set in the planform-customized waverider design method. Their design method introduced the planar shape as a design-driving parameter instead of being determined by the FCC and the ICC to improve the waverider design flexibility. In order to improve the low-speed lift-to-drag ratio of the waverider to satisfy take-off and landing requirements, larger aspect ratio and smaller sweep angle are beneficial to improve the low-speed performance of aircraft. Therefore, two kinds of waverider with the low-speed-friendly planar shape (one with a decrease of leading edge sweep angle and an “∫” -like one) were designed by using the design method of the waverider with a controllable planar shape. Fig. 18 illustrates the two waverider configurations with the low-speed-friendly planar shape. The results showed that customizing the planar shape does not destroy the favorable characteristics of the waverider, i.e., the waverider with a controllable planar shape still has a superior high lift-to-drag ratio in the hypersonic speed range; in addition, the low speed aerodynamic performance is significantly improved as compared to the one without using a low-speed-friendly planar shape, and the performance improvement is achieved at lower cost, because the planar shapes are specified by an engineering point of view instead of complex optimization related to conventional waverider designs.



(a) The isometric view of the design example I

(b) The isometric view of the design example II

Fig. 18 The configuration of the waverider with the low-speed-friendly planar shape [68].

5. The dual/multistage waverider

Hypersonic vehicles can be divided into unpowered gliding and powered cruising vehicles according to whether there is an engine that provides thrust in flight [69]. By combining the advantages of the gliding and cruising flights, Xu et al. [69] proposed a new type of flight trajectory scheme and applied it to the hypersonic gliding-cruising vehicle. The new flight scheme is that the vehicle itself, according to the above concept, is equipped with a ramjet engine with fixed thrust and multiple start functions, and glides and re-enters from outer space at hypersonic speeds; when it arrives within a certain distance from the target or decelerates to a velocity below a specific velocity, the activated ramjet engine propels the vehicle to cruise at hypersonic speeds.

The waverider design process reveals that there is a single corresponding relationship between the shape of the waverider and the design input parameters, that is, a set of input parameters corresponds to the unique shape of the waverider. In the flight trajectory scheme of the hypersonic gliding-cruising vehicle, there are two different main flight phases, namely, the high Mach number gliding flight phase and the low Mach number cruise flight phase. Therefore, in this new flight scheme, the conventional waverider cannot take advantage of its high lift-to-drag ratio. In order to find the most suitable aerodynamic configuration for the gliding-cruising ballistic waverider, the design concept of the dual/multistage waverider was proposed. Its objective was to design the inlet shroud in the gliding stage into the waverider's compression surface.

In 2014, Liu et al. [70] proposed a new waverider design concept, namely a dual waverider. The term 'dual waverider' here refers to a gliding and cruising waverider. Its design idea is to regard the gliding Mach number of the dual waverider as the design Mach number. The inlet shroud is designed as to serve the compression surface of the waverider by using the design method of the cone-derived waverider to ensure that the dual waverider can ride on the shock wave during the gliding phase, and therefore can maintain the waverider characteristics at the design gliding Mach number. On the other hand, using the cruising Mach number of the dual waverider as the design Mach number, the forebody is also designed as the waverider's compression surface by applying the cone-derived waverider's design method to ensure that the dual waverider can still ride on the shock wave after the inlet shroud is cast away. The schematic diagram of the dual waverider design method based on the design theory of the cone-derived waverider is shown in Fig. 19. Liu et al. [70] then verified this waverider design method via numerical simulation, and subsequently compared and analyzed both the dual waverider and the conventional waverider. The study showed that the lift coefficient, drag coefficient and lift-to-drag ratio of the gliding waverider are larger than those of the conventional waverider within the -2° to 6° angle of attack range. Therefore, this methodology is very helpful for the design of the hypersonic glide-cruise vehicle.

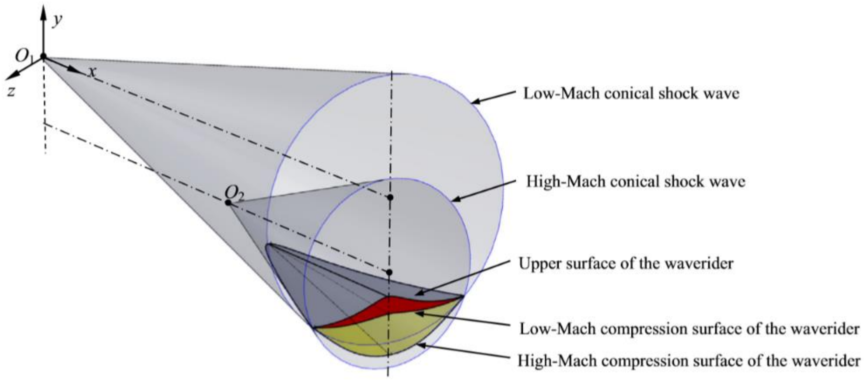


Fig. 19 The schematic diagram of the dual waverider design method based on the design theory of the cone-derived waverider [70].

However, the dual waverider design method proposed by Liu et al. [70] has the following shortcomings: First, the design method of the cone-derived waverider requires that the shock profile curve (SPC) must be an arc, which cannot be easily adjusted to actual needs, and thus complicates to the integrated design of the waverider and the inlet; second, the geometric constraints of this method are very complicated, resulting in the difficulty of designing a suitable dual waverider for the actual mission requirements. In order to solve these problems, Wang [71] adopted the osculating cone theory to design and study the dual waverider, and proposed the dual waverider design methods with constant shock wave angles and variable shock wave angles. The core of these two design methods is to use the osculating cone theory to ensure that the gliding and cruising waverider share a common leading edge.

The design idea of the osculating cone dual waverider with constant shock wave angles is as follows: firstly, the basic curves and design parameters are given, wherein the basic curves include the shock profile curve of the cruising waverider and the trailing edge curve of free-stream surface, and the design parameters include the design Mach numbers and shock wave angles of the gliding and cruising waverider; then, the cruising waverider is designed by the osculating cone theory, and the leading edge of the cruising waverider is obtained; finally, the compression-stream surface of the gliding waverider is designed through the obtained leading edge to ensure that the cruising waverider and the gliding waverider share the same leading edge. The detailed design steps can be found in Ref. [72]. The correctness of this design method is verified by numerical simulation. However, there is flow spillage around the leading edges of the gliding waverider designed by this method. The root cause of this problem is that the design method of the osculating cone dual waverider with constant shock wave angles adopts the following assumptions: the osculating planes of the cruising waverider and the gliding waverider at any point on the trailing edge curve of free-stream surface of the dual waverider are in the same plane, and the osculating cone axis of the gliding waverider in the osculating plane is the same as that of the cruising waverider.

In order to remedy the above-mentioned flow spillage, Wang [71] proposed the design method of the osculating cone dual waverider with variable shock wave angles. The design idea is as follows: firstly, the basic curves and design parameters are given, and the cruising waverider is designed by the osculating cone theory, and the leading edge of the cruising waverider is obtained; then, according to the leading edge of the cruising waverider and the shock profile curve of the gliding waverider, the respective shock wave angle are determined in each of the osculating planes, thereby obtaining the basic flow field of the gliding waverider by the osculating cone theory; finally, the streamline tracking method is used to generate the compression-stream surface of the gliding waverider in the basic flow field of the gliding waverider. The detailed design steps can be found in Ref. [73]. The correctness of this design method is verified by the CFD method. From the numerical simulation results, it can be seen that there is no flow spillage around the leading edges of the gliding waverider designed by this method, which indicates that the design method has achieved the original design objective.

In 2017, Liu et al. [74] developed the design concept of the dual waverider, and put forward the design method of the multistage waverider. However, the design idea of the multistage waverider is different from that of the dual waverider, and the core of its design is to generate several compression-stream surfaces of the multistage waverider in a plurality of conical flow fields with the same shock angle and different Mach numbers. It can be seen that the multistage waverider design method proposed by Liu et al. [74] can also be regarded as a design method for the variable Mach number waverider. This multistage waverider can be used in two transfiguration flight strategies: one is the application of smart materials and structures in the manufacture of the multistage waverider. By using smart materials, the multistage waverider can appropriately change its configuration according to flight mission requirements, that is, to shape the compression-stream surface, in such a way that the waverider characteristics can be maintained at each flight Mach number. Another transfiguration flight strategy is to use the compression-stream surface at different stages as cowlings when the multistage waverider is used as a gliding vehicle, to ensure that the multistage waverider can always use the compression-stream surface to maintain the waverider characteristics at different flight Mach numbers. It should be noted that the implementation of the former or other transfiguration flight strategies changes the configuration. Therefore, this multistage waverider can be regarded as a morphing waverider. The supersonic axisymmetric conical flow field used in the design of the multistage waverider is shown in Fig. 20. The specific steps of the multistage waverider design method can be found in Ref. [75]. Numerical studies of this kind of waverider and of the traditional single-stage waverider were conducted. The results indicated that the multistage waverider design method can effectively solve the problem of aerodynamic performance deterioration of the waverider in the off-design state, and ensure that the aircraft always maintains the optimal flight state.

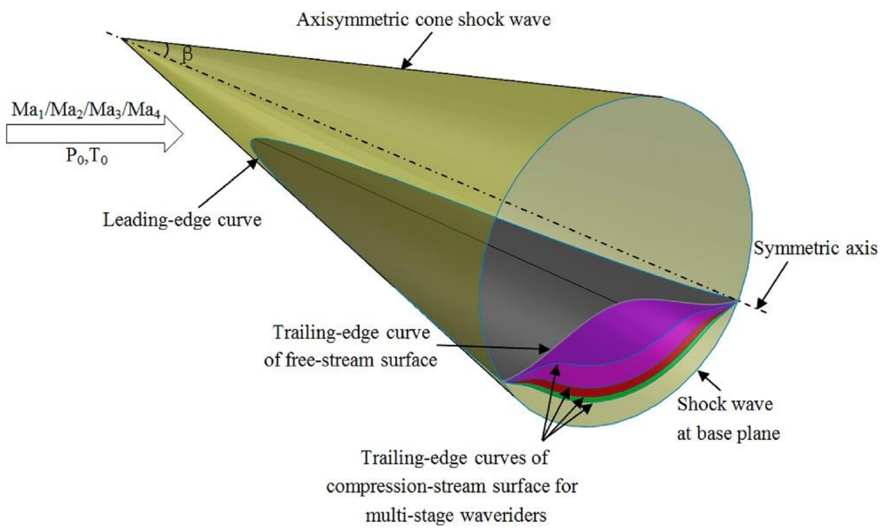


Fig. 20 Basic design principle of the multistage waverider [75].

In the above schemes, the compression-stream surface of the dual/multistage waverider are designed for several discrete design Mach numbers, and the waverider characteristics are realized by using the corresponding compression-stream surface at different flight Mach numbers. This type of design method can obviously improve the aerodynamic performance of the waverider under the corresponding design Mach numbers, but it is only a compromise solution, that is, the waverider characteristics cannot be effectively guaranteed when flying between different design Mach numbers.

6. The morphing waverider

The term “morphing aircraft” refers to various air vehicles and vehicle components that meet the requirements of planned and unplanned multipoint missions [76]. It is considered to be a promising enabling technology for the future, next-generation aircraft [77]. Compared with the traditional aircraft, the morphing aircraft can operate under different flight conditions, which expands its flight envelope [78][79]. They can bridge the design contradiction between high-speed and low-speed flight. Therefore, the use of morphing technologies to enable the waverider to operate over a wide-speed range is quite attractive.

In 2003, Bowcutt [80] designed a wing-body aircraft that includes a pair of leading edges, a pair of trailing edges and a pair of waverider flaps, as shown in Fig. 21. Among them, the special configuration of waverider flaps is intended to expand the range of flight Mach numbers and angles of attack while keeping the wing bow shock wave always attached to leading edges. In other words, the purpose of the waverider flaps being articulated is to define an almost infinite number of optimal shapes for the entire range of Mach number and angle of attack required for the wing-body aircraft to operate. In the detailed description of the preferred embodiments, he also pointed out that port and starboard waverider flaps can be actuated independently for greater lateral/directional dynamic stability and control.

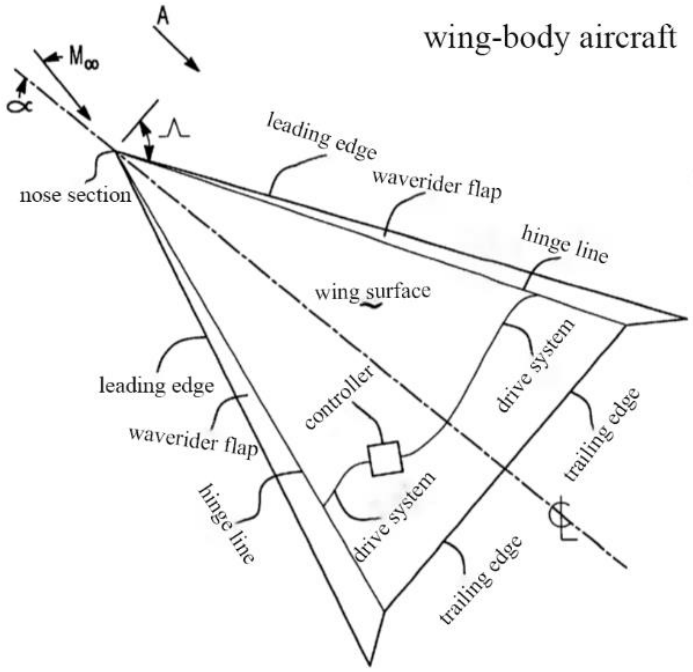
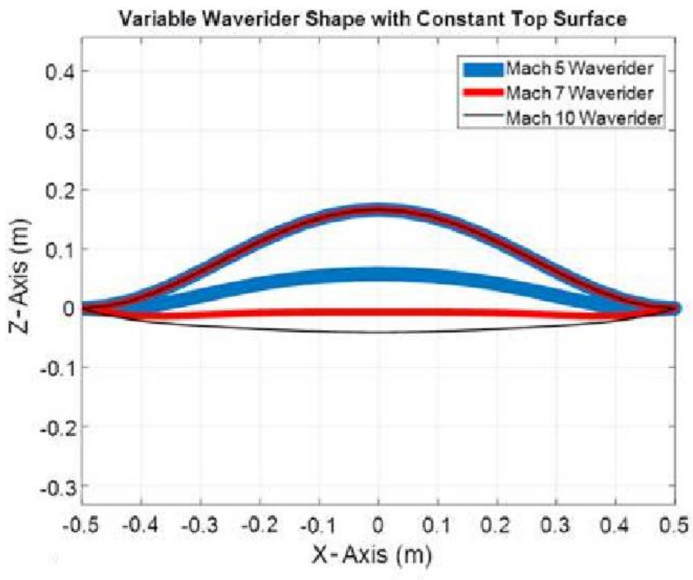
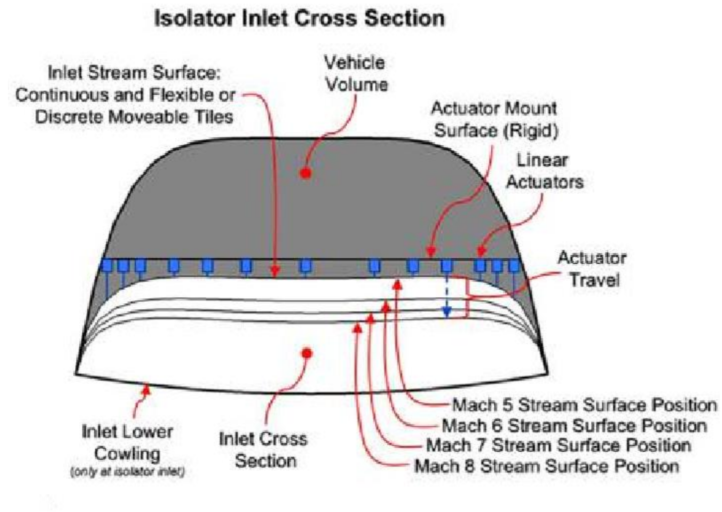


Fig. 21 The delta wing with waverider flaps as leading edge [80].

In 2016, Maxwell [81] proposed a morphing waverider concept that uses a morphing bottom surface to provide on-design waverider aerodynamic performance across a wide Mach number range. The design idea is based on the fact that the total area of the waverider's lower surface stays approximately constant in the hypersonic regime even though the stream surface curvature may vary drastically with the Mach number. On this foundation, the Naval Research Laboratory developed a family of morphing waveriders with a constant leading edge and a constant top surface, as well as a morphing bottom surface [82][83]. Fig. 22 illustrates the general concept of the shape morphing waverider.



(a) waverider projectile



(b) waverider scramjet inlet

Fig. 22 The variable waverider shapes [82][83].

Next, Phoenix et al. [82][83] investigated the feasibility of the morphing waverider concept and studied the performance advantages of the morphing hypersonic waverider. They used a Finite Element Model (FEM) to model the morphing surface and calculated the resulting morphing accuracies for various control configurations. They designed a Mach 10 waverider to enable shock attachment from Mach 10 to 5 and identified a control set that can accurately control the morphed surface. They analyzed the optimal control points set (actuator locations) and performed a sensitivity analysis using the Q-DEIM-algorithm sensitivity analysis. The study showed that the performance of the ideal morphing waverider is significantly improved and a two-control-point or six-control-point system provides 90% and 97% of the ideal control system performance improvements.

It should be noted that at this stage of the above analysis, only the bottom surface of the back cross-section is evaluated, and the full 3D surface is not addressed. Therefore, in order to further determine the validity of the morphing waverider concept, Phoenix et al. [84] also chose a 3D waverider model with realistic system stiffness and geometric constraints to evaluate the locations and number of actuators required to deliver the needed morphing accuracy. The 3D waverider model that is composed of plate elements with two different thickness and spring elements connections is shown in Fig. 23. The study indicated that for the six inches wide morphing hypersonic waverider that was operated from Mach 5 down to Mach 3.5, the surface errors for the cases with 5 and 14 control points were reduced by 87% and 95% respectively. In addition to the research on the morphable waverider design theory, they also carried out research on the use of a morphable waverider for entry vehicles and scramjet engine intake manifolds [8][85][86][87][88].

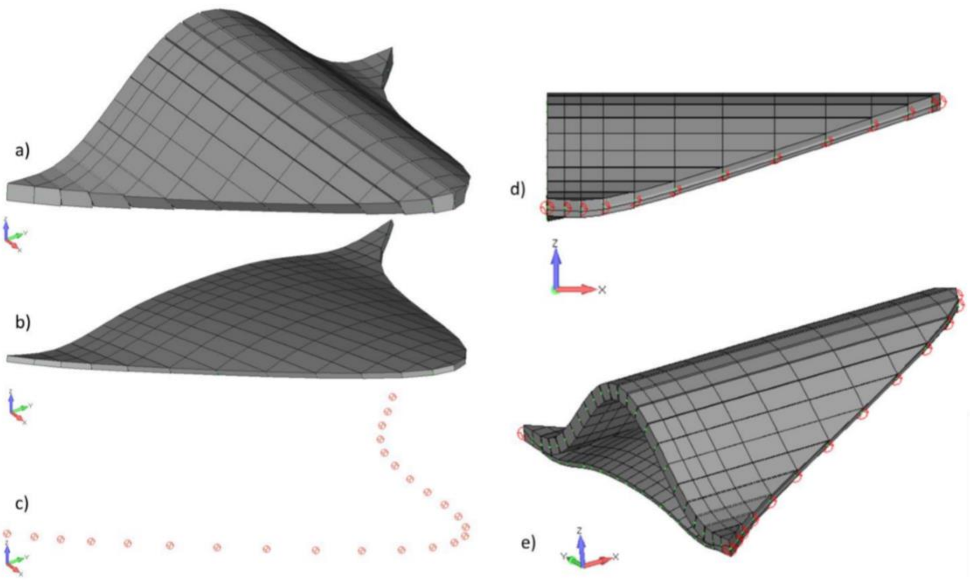


Fig. 23 The 3D waverider model with a) Top Surface, b) Bottom Surface, c) Spring Element Connection between Top and Bottom Surface, d) Combined Model Side view, and e) Isometric Combined Model View [84].

7. Other wide-speed-range waverider designs

In addition to the above-mentioned design schemes of waveriders with a wide-speed range, there are the following additional design schemes.

In 2011, Takama [89] proposed to improve the ideal waverider’s low-speed aerodynamic characteristics. Its configuration is shown in Fig. 24. He applied numerical simulation to obtain the subsonic and hypersonic aerodynamic performance of this configuration. The results showed that the addition of outer wings can increase the ideal waverider's lift-to-drag ratio in the subsonic regime, while having little effect on its hypersonic performance. Thus, this design concept can be promising for the design of wide-speed-range hypersonic waveriders.

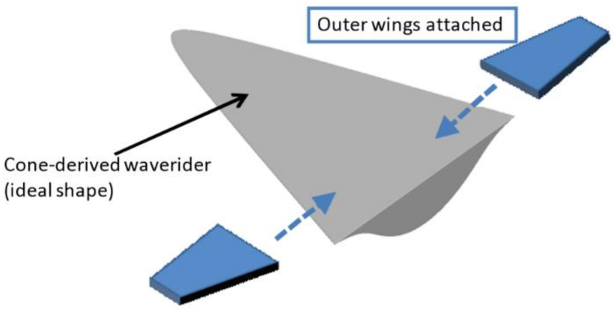


Fig. 24 The practical waverider attached to outer wings [89].

8. Discussion

The aerodynamic characteristics of an aircraft are closely related to its flight speed range. As shown in Figs.25 and 26, the optimized aerodynamic configurations are quite different in different speed ranges. Therefore, combining the configuration characteristics of the aircraft in different flight speed ranges can be used as a development idea to find the optimal wide speed range waverider configuration.

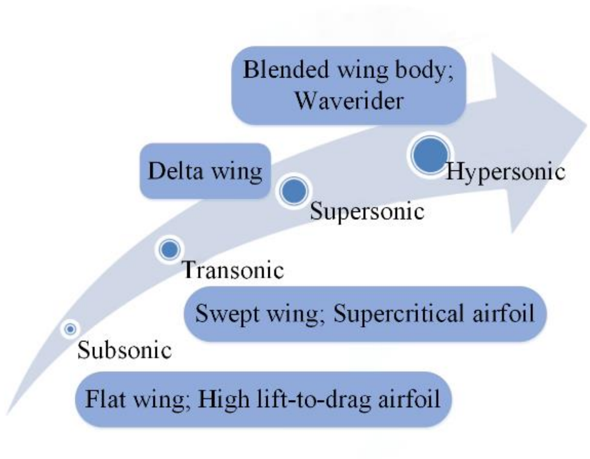


Fig. 25 Optimal aerodynamic configuration at different speed ranges.

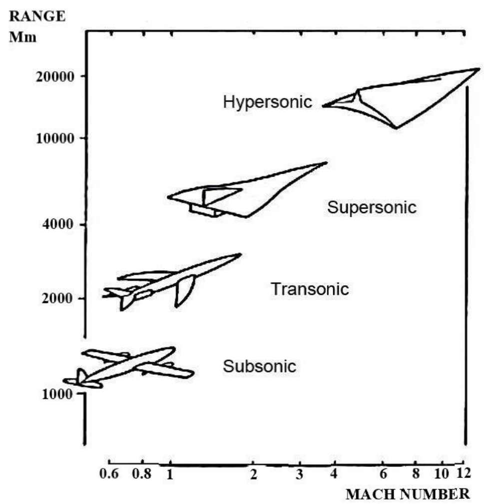


Fig. 26 The aircraft pedigree [1].

To this end, a good understanding of the non-linear behavior of the vortex generated lift as discussed in Ref. [25] and Refs.[55-63], is very important. As discussed in Ref. [90], the aerodynamic performance of the waverider is closely related to the aerodynamic state of its leading edge, that is, to the average aspect ratio of the waverider. When the leading edge of the waverider is subsonic, the flow field exhibits typical characteristics of a subsonic flow field, and its lift is mainly derived from leading edge vortices near the leading edge of the upper surface. On the other hand, when the leading edge is supersonic, the compression effect of the shock near the leading edge becomes the main source of the lift of the waverider. Therefore, another development idea of the wide-speed range waverider is to analyze and study the characteristics of vortex flow around the waverider, and then design a waverider which can effectively employ the vortex effect to improve the subsonic performance and the shock effect to improve the super/hypersonic performance, respectively. For example, the study in Ref. [66] is a design that combines vortex lift and compression lift to improve the aerodynamic performance of the waverider over a wide-speed range.

9. Conclusions

In this survey, the research progress on the design methodology of wide-speed-range hypersonic vehicles based on the design method of waveriders has been summarized, and five typical design schemes have been mentioned, namely the “combined” wide-speed range waverider, the variable Mach number waverider, the vortex lift waverider, the dual/multistage waverider, and the morphing waverider. Their design ideas and characteristics have been introduced and analyzed. For the further development of the wide-speed range waverider, the following conclusions are important:

- Considering that the flight characteristics at different flight speeds are quite different, it will be important to effectively combine the aerodynamic characteristics of the aircraft in different flight speed ranges.
- The method of applying the vortex lift concept to the design of the waverider still requires further study. The generation, development and influencing factors of the vortex effect need to be more deeply analyzed.
- The morphing technologies and the recent advances in smart materials research, actuation

technology, constitutive laws and modeling, optimization and control, and failure prediction, will become increasingly important for the design of the wide-speed-range hypersonic vehicle.

Conflict of interest statement

The authors declare there is no conflict of interest regarding the publication of this paper.

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