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An overview of research on waverider design methodology

Feng Ding[a,b,*], Jun Liu[a,b], Chi-bing Shen[a,b], Zhen Liu[a,b], Shao-hua Chen[a,b], Xiang Fu[a,b]

[a] College of Aerospace Science and Engineering, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China
[b] Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China

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ABSTRACT

A waverider is any supersonic or hypersonic lifting body that is characterized by an attached, or nearly attached, bow shock wave along its leading edge. As a waverider can possess a high lift-to-drag ratio as well as an ideal precompression surface of the inlet system, it has become one of the most promising designs for air-breathing hypersonic vehicles. This paper reviews and classifies waverider design methodologies developed by local and foreign scholars up until 2016. The design concept of a waverider can be summarized as follows: modeling of the basic flow field is used to design the waverider in the streamwise direction and the osculating theory is used to design the waverider in the spanwise direction.

1. Introduction

A waverider is any supersonic or hypersonic lifting body that is characterized by an attached, or nearly attached, bow shock wave along its leading edge. Because of the excellent aerodynamic configuration of the waverider, it has always attracted the attention of researchers, especially aerodynamic configuration designers [1]. Comparison studies [2,3] have revealed that at the same lift coefficient, the waverider (shown in Fig. 1) has a higher lift-to-drag ratio than a conventional lifting body (shown in Fig. 2), as shown in Fig. 3. Furthermore, at the same lift-to-drag ratio, the former has a higher lift coefficient than the latter, as also shown in Fig. 3. The waverider often used in the aerodynamic design of hypersonic vehicles has another advantage: an ideal precompression surface of the inlet system. Because the leading-edge shock wave generated by the waverider can precompress the air and limit the high-pressure air between the compression-stream surface and the shock wave escaping to the upper surface, the waverider can capture a much greater amount of air.

The core of the waverider design methodology is the design of the streamlines constituting the compression-stream surface of the vehicle. The shape and pressure distribution of a streamline are determined by the basic flow field. The overall design procedure of a waverider involves designing and solving of the basic flow field, tracing of a group of streamlines in the basic flow field, and lofting of all the streamlines to obtain the compression-stream surface of the vehicle. Investigation of a waverider design methodology can be divided into the following five tasks: 1) selection and design of the basic flow field in the flow direction, 2) solving of the basic flow field, 3) streamline tracing, 4) application of the osculating theory in the spanwise direction, and 5) remodel design for a specific purpose.

2. Types of basic flow fields

A waverider is usually constructed in a steady inviscid supersonic flow field (or a flow field composed mainly of supersonic flow); this inviscid flow field is termed the basic flow field. The characteristics of the basic flow field govern the shape and performance of a waverider in the flow direction; therefore, the basic flow field is the core of the design of a waverider in the flow direction. Consequently, researchers have been attempting to widen the design space of a waverider by establishing choices of basic flow fields in which the waverider is generated, and the aim of such studies has been to improve the aerodynamic performance of hypersonic vehicles.

Basic flow fields used for waverider design can be classified into two types: steady two-dimensional (2D) planar or axisymmetric supersonic flow fields and three-dimensional (3D) supersonic flow fields. Since 2D planar or axisymmetric flow fields can be calculated easily by fast calculation methods such as the analytical method, the method of characteristics (MOC), and the space-marching finite difference method, most of the basic flow fields used for rapid design and optimization of waveriders are of the 2D planar or axisymmetric type.

* Corresponding author. College of Aerospace Science and Engineering, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China.
E-mail address: dingcuifengdcf@163.com (F. Ding).

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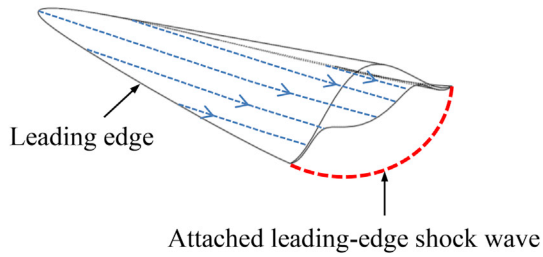


Fig. 1. Waverider configuration [2,3].

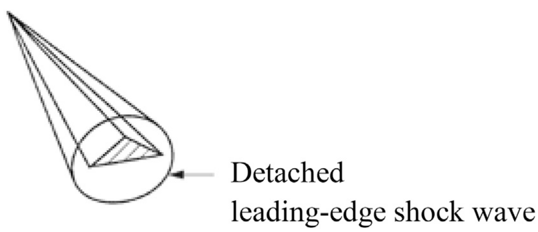


Fig. 2. Lifting-body configuration [2,3].

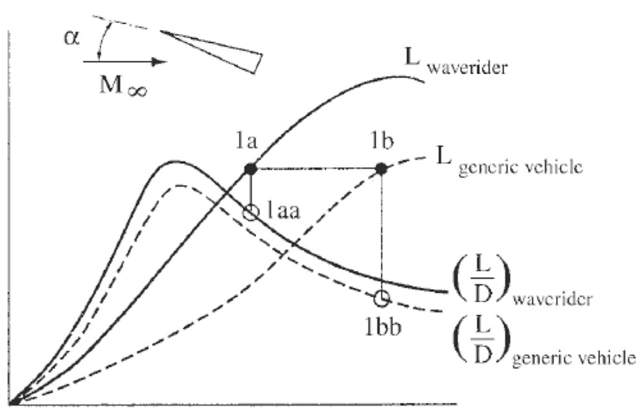


Fig. 3. Comparison of lift and L/D curves between waverider and generic lifting-body vehicle [2,3].

2.1. Inviscid 2D planar basic flow fields

The supersonic flow around a wedge is a typical 2D planar flow field. When Nonweiler [4] first proposed the waverider design concept in 1959, he employed flows past a wedge to generate the first waverider in the history of aerospace science and technology. Because the cross section of this type of waverider has a "Λ" shape, this type waverider is termed the "Λ" waverider, and it is also known as the wedge-derived waverider, as shown in Fig. 4. Although the "Λ" waverider is of low practical value because of its low volumetric efficiency, its design concept is pioneering, because of which it provides the future research direction for hypersonic vehicle configurations.

Furthermore, the "Λ" waverider is also named the V-shaped wing by Zubin and Ostapenko [5–7], Ostapenko [8], Ostapenko and Simonenko [9], Maksimov and Ostapenko [10], Zubin et al. [11] from Sussian Moscow State University, and the main design parameters of the V-shaped wing are shown in Fig. 5. Furthermore, there has been widespread investigation of the flow over V-shaped wing [5–10]. Both the theoretical and experimental results showed that at supersonic or hypersonic speed a V-shaped wing is more efficient in flow regimes with a shock attached to the leading edges as compared to a equivalent planar triangular wing, and the former has a larger lift-to-drag ratio than the later (given the specific volumes and lift coefficients of the two configurations being equal) [8].

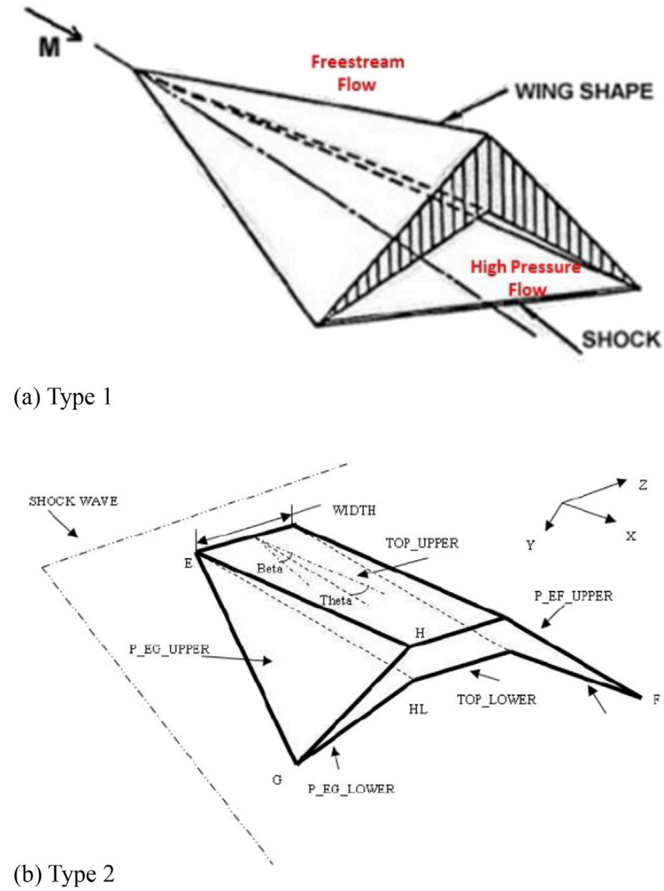


Fig. 4. Wedge-derived waverider ("Λ" waverider) [95].

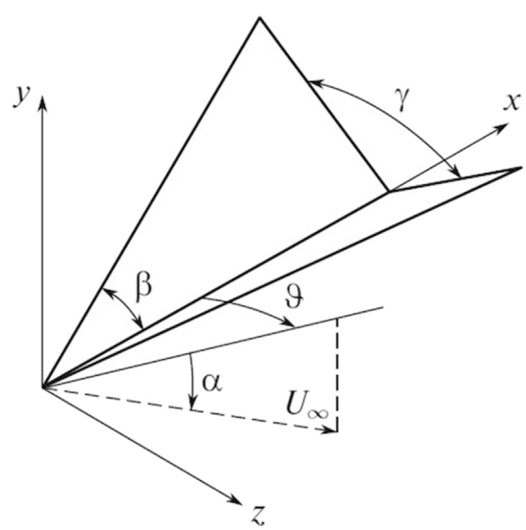


Fig. 5. V-shaped wing [10].

Mazhul and Rakhimov [12,13] investigated another type of waverider that was also generated from flows past a wedge. For this type of waverider, the projection curve of its leading edge on the base plane is a power-law curve; therefore, it is termed the power-law-shaped waverider, as shown in Fig. 6.

In 2010, Mazhul [14] from the Russian Academy of Science first employed a kind of 2D curved surface compression flow combined with

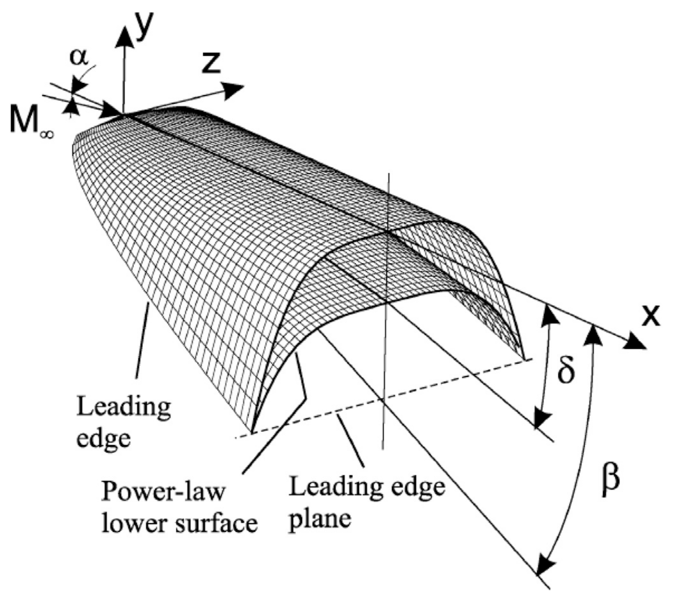


Fig. 6. Power-law-shaped waverider [13].

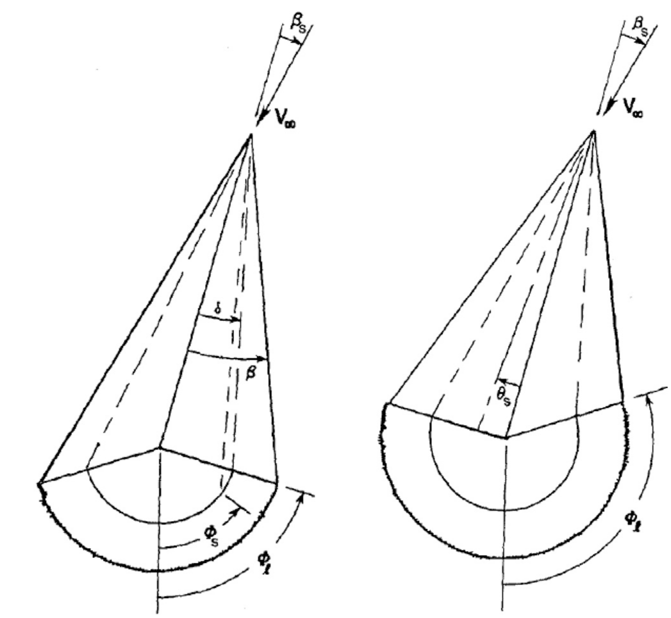
an oblique shock wave and isentropic compression flow to design the waverider shown in Fig. 7; then, he investigated the off-design performance of this type of waverider by using a finite-volume solution of Euler equations by means of higher-order total-variation-diminishing (TVD) Runge–Kutta schemes.

2.2. Inviscid 2D axisymmetric basic flow fields

2.2.1. Inviscid conical basic flow field

The supersonic flow around a cone at a zero angle of attack, which is known as a conical flow field, is a typical 2D axisymmetric basic flow field. In 1968, Jones et al. [15] first used this kind of flow field to design a waverider known as the cone-derived waverider. The conical flow field is by far the most widely used basic flow field for waveriders, and the cone-derived waverider has become the most widely used waverider owing to the ease of its calculation and better volumetric efficiency than wedge-derived waverider on account of the concave streamlines being closer to the shock wave [16].

According to whether or not the leading-edge curve passes through the axis of symmetry of the conical flow field, the cone-derived waverider can be classified into two types: an idealized cone-derived waverider and a general cone-derived waverider. The leading-edge curve of the idealized cone-derived waverider can pass through the axis of symmetry of the conical flow field. According to whether the dihedral angle is positive or negative, the idealized cone-derived waverider can be divided into two types—type 1 and type 2, respectively—as shown in Fig. 8(a) and (b), respectively. The leading-edge curve of the general cone-derived waverider is usually located below the axis of symmetry of the conical flow



(a) Type 1
(Negative dihedral angle)

(b) Type 2
(Positive dihedral angle)

Fig. 8. Idealized cone-derived waverider [96].

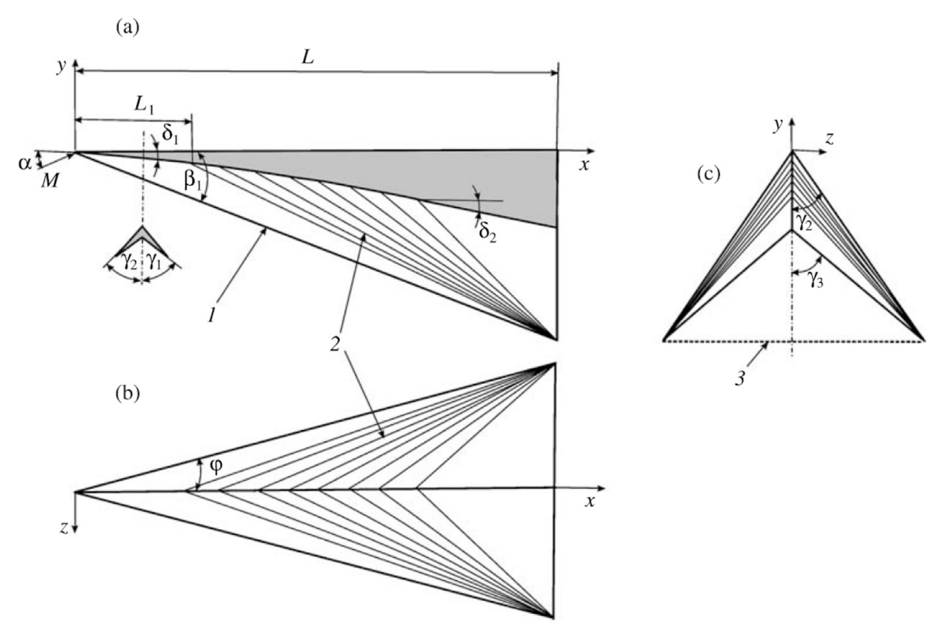


Fig. 7. Waverider generated from 2D curved compression flow field [14].

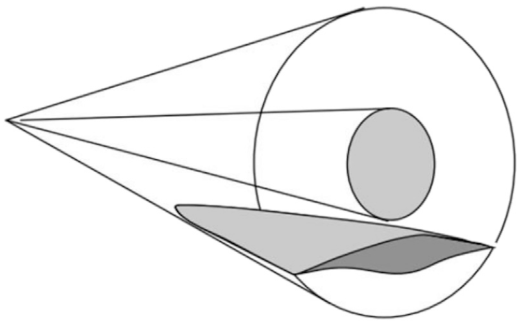


Fig. 9. General cone-derived waverider [95].

field, as shown in Fig. 9.

2.2.2. Inviscid curved conical basic flow field

In 1988, Corda [17] from the University of Maryland College Park first used the flow over a minimum-drag body at a zero angle of attack as the basic flow field to design a waverider. In order to ensure generation of a completely supersonic flow with an attached shock wave when the minimum-drag body traveled at a supersonic speed—which would also reduce the computational cost—several pointed power-law bodies were selected as the minimum-drag bodies in the study. Then, a series of viscous optimized waveriders were designed from flows over minimum-drag bodies, and their flow characteristics and performances were compared with those of conventional cone-derived waveriders. The comparison results showed that the lift-to-drag ratios of the waveriders designed from the flow fields over minimum-drag bodies were equivalent to or better than those of the cone-derived waveriders.

In 2006, Mangin et al. [16] from the French Centre National de la Recherche Scientifique (CNRS) used flows around blunt power-law bodies as the basic flow field to design waveriders. The study results showed that although the waverider generated from flows past blunt power-law bodies had a slightly higher (7% higher) lift-to-drag ratio than the cone-derived waverider, the volume of the former increased by more than 20%.

In 2006, Geng et al. [18] from the Institute of Mechanics of the Chinese Academy of Sciences employed a kind of axisymmetric curved surface compression flow combined with a conical shock wave and near-isentropic compression flow to design a waverider. The study results indicated that this kind of waverider can achieve higher pressure recovery to meet the air-breathing requirement of a vehicle with engine integrated design.

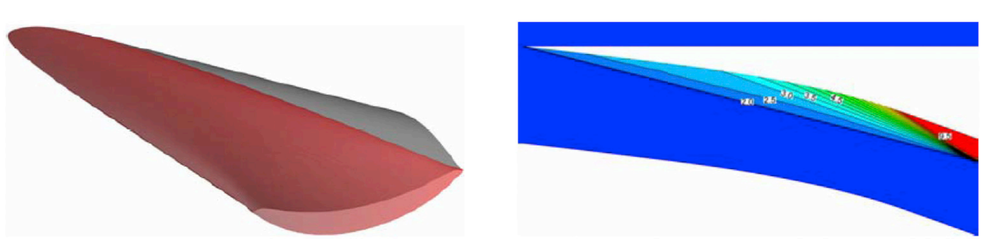
In 2009, He et al. [19] from the China Aerodynamic Research and Development Center used flows around a concave curved cone as the basic flow field to design waveriders. This kind of waverider is termed the curved-cone-derived waverider; the designed waverider and its attached leading-edge shock wave are shown in Fig. 10(a), and the corresponding pressure contour of the symmetry plane is shown in Fig. 10(b). The curved-cone-derived waverider has a higher volumetric efficiency of the airframe and better air compression ability of the engine in comparison to the cone-derived waverider; thus, this kind of waverider is much better suited for airframe-engine integration.

In 2015, Ding et al. [20] from the National University of Defense Technology proposed a novel waverider generated from axisymmetric supersonic flows past a pointed von Karman ogive. This kind of waverider is termed the von Karman waverider, and its principle is illustrated in Fig. 11. In the study of Ding et al. [20], a conventional waverider used as a comparison model was designed using the conventional conical basic flow field past a cone, and the performances of these two waveriders (i.e., the novel and conventional waveriders) were numerically predicted in order to analyze the differences between them. The comparison results showed that the novel waverider possessed higher lift-to-drag ratios, lower trim drag, and a larger internal volume than the conventional waverider; the results also demonstrated that the proposed basic flow field past a pointed von Karman ogive can provide greater flexibility in the design and optimization of hypersonic waverider vehicles. The same authors subsequently performed another set of comparisons [21], whose results showed that the novel waverider possessed lower drag and higher lift-to-drag ratios, whereas the conventional waverider had a larger internal volume and volumetric efficiency. Both these comparative studies showed that the novel von Karman waverider generated from axisymmetric supersonic flows past a pointed von Karman ogive possessed higher lift-to-drag ratios than the conventional cone-derived waverider generated from axisymmetric supersonic flows past a cone.

2.2.3. Inviscid internal conical basic flow field

In 2000, Goonko et al. [22] from the Russian Academy of Sciences studied a new type of waverider derived from supersonic axisymmetric flows inside constricting ducts, specifically conical trumpet ducts. In such a duct, an initial shock wave is generated from its leading edge, and the compression flow downstream of this shock wave has streamlines converging toward the flow axis. This flow is a kind of internal conical flow, and it was chosen as the basic flow for the design of the waverider, which was termed the convergent-flow-derived waverider, or the convergent waverider, in the study of Goonko et al. [22]. The design principle of the convergent waverider is shown in Fig. 12. A class of convergent waveriders was compared with known types of waveriders derived from uniform flows behind plane oblique shock waves or from divergent flows behind axisymmetric conical shock waves. The comparison results indicated that the convergent waveriders have better air compression ability of the engine, a higher lift coefficient of the airframe, and lower integral heat flux through the wall surfaces of the waverider but a lower lift-to-drag ratio of the airframe.

In 2006 and 2008, respectively, You et al. [23] and You [24], from the Nanjing University of Aeronautics and Astronautics, designed a waverider derived from the internal conical flow field, termed the internal waverider. Subsequently, He and Ni [25] and He et al. [26] used the



(a) Designed curved-cone-derived waverider and its attached 3D shock wave structure under design condition

(b) Pressure contour in symmetry plane of designed curved-cone-derived waverider

Fig. 10. Curved-cone-derived waverider, attached shock wave, and pressure contour in symmetry plane [19].

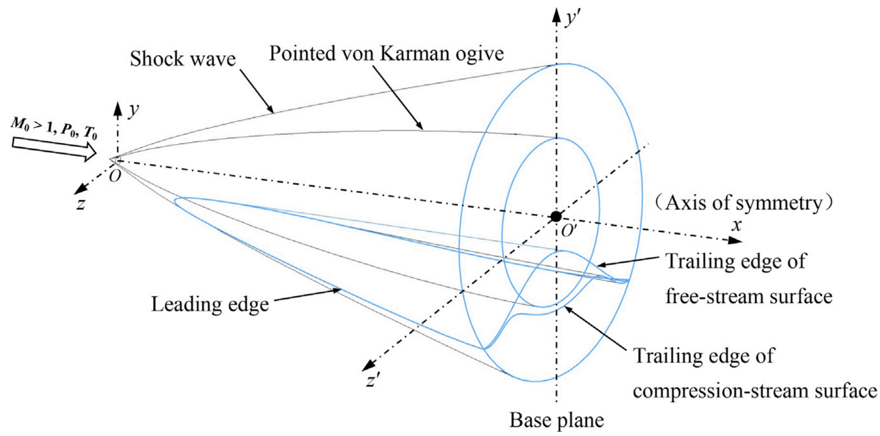


Fig. 11. Principle of von Karman waverider [20].

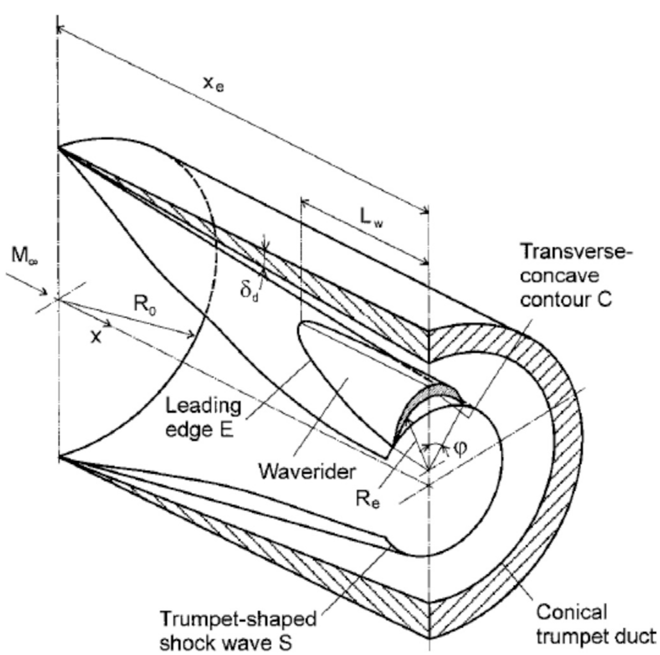


Fig. 12. Design of convergent waverider derived from axisymmetric flow inside a constricting conical duct [22].

Internal Conical Flow “A” (ICFA) [27] with a straight shock wave as the basic flow field to develop a class of waveriders termed osculating inward turning cone waveriders (OIC waveriders for short); the typical configuration of this kind of waverider is shown in Fig. 13. Numerical and experimental studies of this kind of waverider were conducted under both design and off-design conditions. The results indicated that this kind of waverider has small flow spillage under both design and off-design conditions.

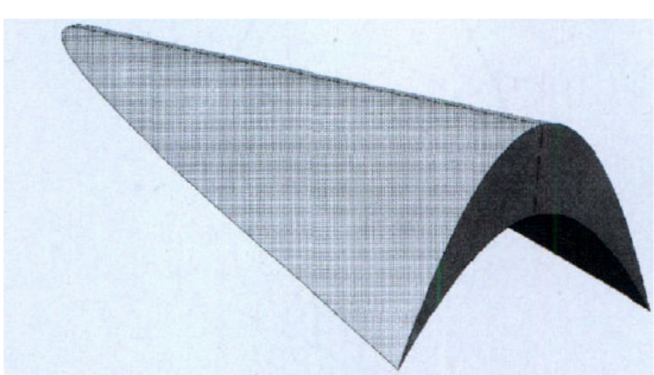


Fig. 13. 3D view of osculating inward turning cone (OIC) waverider [25].

2.3. Inviscid 3D basic flow field

In order to improve the performances of waveriders, some researchers also have been attempting to use some another inviscid flows other than inviscid axisymmetric flows, known as inviscid 3D flows, to expand the choice space for basic flow fields. There are two types of 3D basic flow fields: flows past a quasi-cone and flows past a wedge-cone body.

2.3.1. Inviscid basic flow field around quasi-cone

As early as 1979, Rasmussen [28,29] from the American University of Oklahoma first attempted to use three inviscid basic flow fields around a quasi-cone: flow past a circular cone at a small angle of attack, flow past an elliptic cone at a zero angle of attack, and flow past an elliptic cone at a small angle of attack. As the leading edge of the waveriders considered in Rasmussen's study passed through the axis of symmetry of the quasi-cone, the waverider configurations inherited the shapes of the inclined

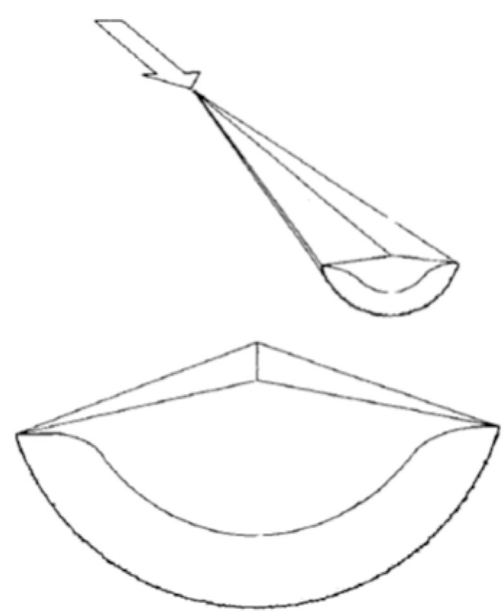


Fig. 14. Inclined-circular-cone waverider with attached leading-edge shock wave [29].

circular cone, elliptic cone, and inclined elliptic cone; thus, these waveriders were termed the inclined-circular-cone waverider, elliptic-cone waverider, and inclined-elliptic-cone waverider, respectively. The configurations of these three waveriders with an attached leading-edge shock wave are shown in Figs. 14–16, respectively.

In 1982, Rasmussen et al. [30], again from the University of Oklahoma, and Jischke et al. [31] from the Air Force Armament Laboratory continued to test the aerodynamic force, aerodynamic moment, and surface pressure distribution characteristics of such waveriders derived from basic flow fields around a quasi-cone. In 1988, Lin and Rasmussen [32] continued to attempt using basic flow fields around ogival bodies with noncircular cross sections and designed a type of waverider with a combined transverse and longitudinal curvature. Then, in 1995, Lin and Luo [33] performed optimization of the design of this type of waverider.

In 2007, Cui and Yang [34] and Cui et al. [35] from the Chinese Academy of Sciences, analyzed the effects of the cross-sectional shape and the width-to-height ratio of the generating elliptic cone on the performance of waveriders derived from quasi-conical flow fields around

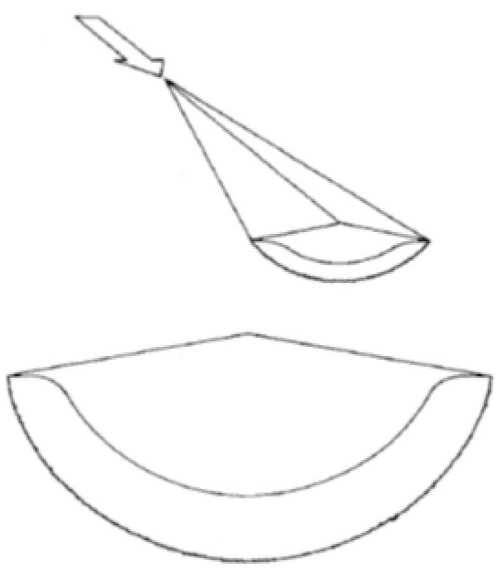


Fig. 15. Elliptic-cone waverider with attached leading-edge shock wave [29].

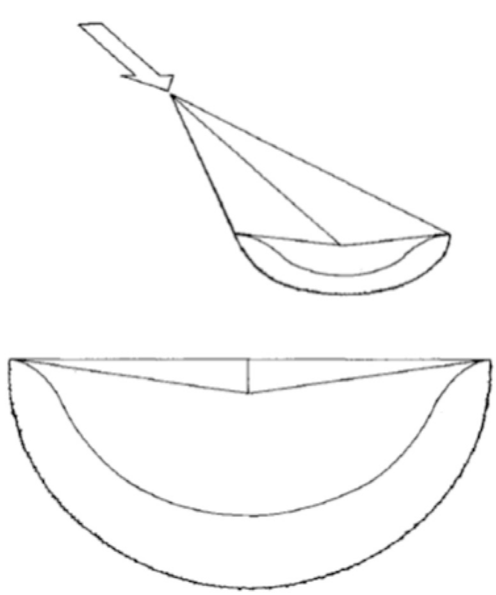


Fig. 16. Inclined-elliptic-cone waverider with attached leading-edge shock wave [29].

elliptic cones. The design principle of this type waverider is shown in Fig. 17. The study results indicated that the lift-to-drag ratios of the elliptic-cone-derived waveriders were higher than those of the cone-derived waveriders; furthermore, a minimum-drag configuration and maximum-lift-to-drag ratio configuration could be obtained when the width-to-height ratios of the generating elliptic cone were 1:1.5 and 1.5–1.618, respectively.

In 2016, Liu et al., [36,37] from the China Academy of Aerospace Aeronautics extended the basic flow field from simple flows such as conical flow and axisymmetric flow to the more general flows. They used a blunt elliptic cone and a combined cone with an angle of attack as the basic bodies to generate two types of 3D basic flow fields; these basic flow fields were, in turn, used to generate two types of waveriders, termed the blunt elliptic cone waverider and combined cone waverider, respectively. The blunt elliptic cone and combined cone with an angle of attack are shown in Figs. 18 and 19, respectively. Then, the two waveriders were compared with the conventional cone-derived waverider. The comparison results indicated that the 3D basic flow field had a significant effect on the performance of the waverider and that this effect was fundamental. In order to design a good 3D flow field waverider, it is necessary to test different geometric shapes of the basic body, to determine a suitable basic flow field for the waverider design, and to establish a standard basic flow field for the design of a high-performance waverider.

2.3.2. *Inviscid basic flow field around wedge-cone body*

In 1994 and 1995, Takashima and Lewis [38,39] from the University of Maryland in the United States first used a 3D flow field around a wedge-cone body as shown in Fig. 20 in order to generate a waverider, which was termed the wedge-cone waverider. Their study results indicated that the wedge-cone waverider provided a higher volume than the cone-derived waverider while also providing a comparable lift-to-drag ratio. In 2013, Ming [40] from the Nanjing University of Aeronautics and Astronautics conducted a study on the design method and performance characteristics of the wedge-cone waverider, and the study results confirmed that this waverider had the advantages of both the wedge-derived waverider and the cone-derived waverider.

2.4. *Other three-dimensional basic flow fields*

It is interesting to note that some researchers used inviscid chemically reacting equilibrium flow or viscous flow as the basic flow field for waverider design.

The first study of this kind was conducted by Mclaughlin [41] and Anderson et al. [42] from the University of Maryland in the United States. In 1990 and 1992, respectively, these authors studied inviscid chemically

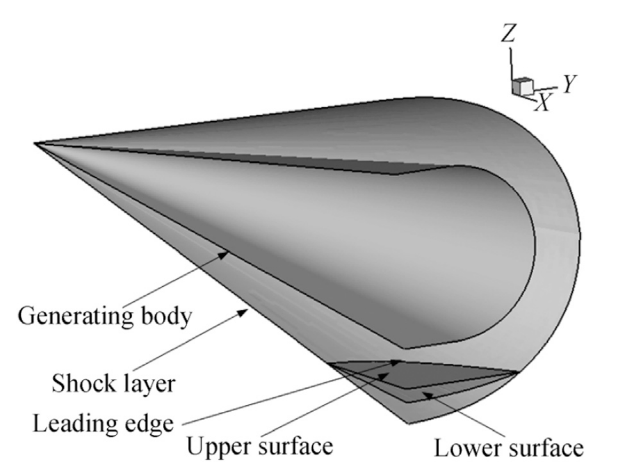


Fig. 17. Design principle of waverider derived from quasi-conical flow fields around elliptic cone [34].

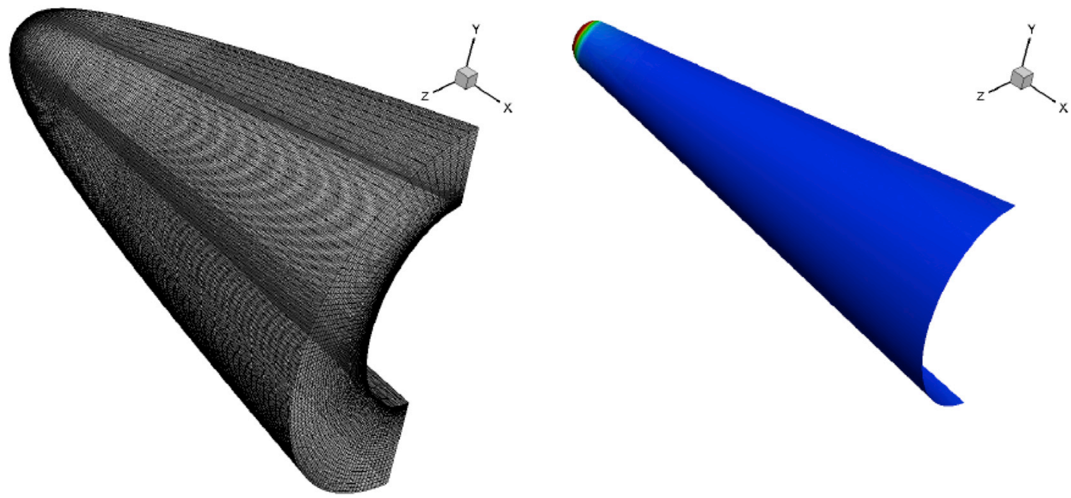


Fig. 18. Mesh and pressure distribution of elliptic cone [36].

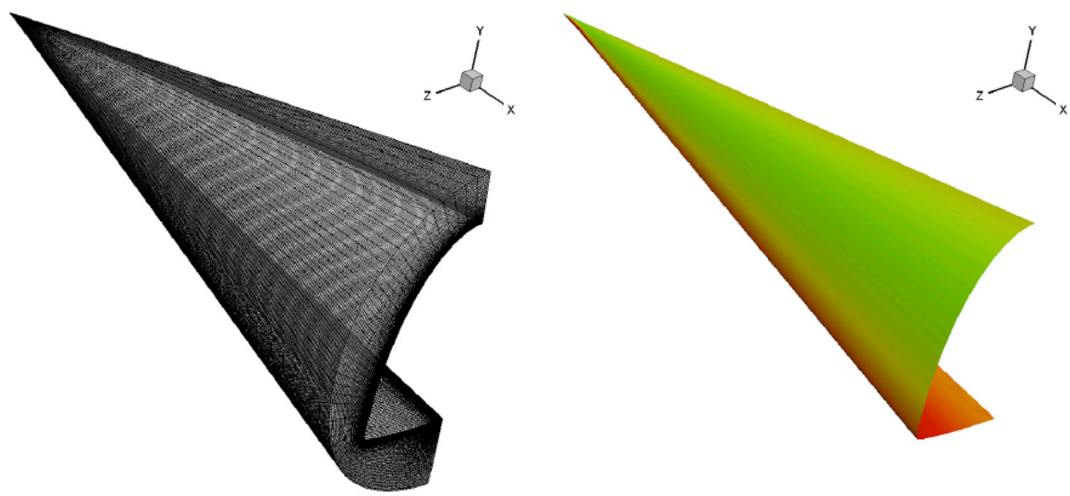


Fig. 19. Mesh and pressure distribution of combined cone [36].

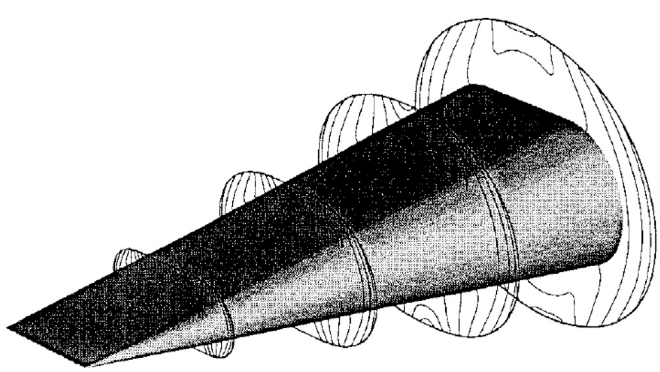


Fig. 20. Wedge-cone generating body and pressure contours around the body [39].

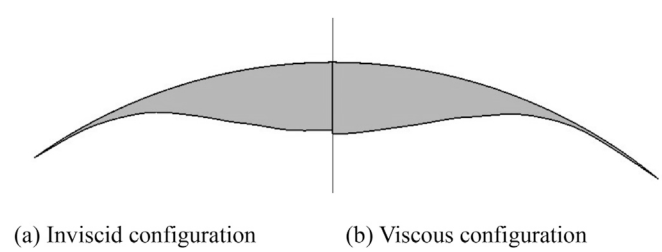


Fig. 21. Comparison of rear views of two waveriders generated from inviscid and viscous flow fields [43].

reacting equilibrium flow as the basic flow field and developed waveriders by considering this flow. Anderson et al. [42] also pointed out that when the Mach number of the basic flow field is less than 25, it is reasonable to consider the air as a complete gas without having to consider the chemical reaction.

In 2014, Li and Zhou [43] used the commercial computational fluid dynamics (CFD) software ANSYS Fluent [44] and the one-equation turbulence model [45] to solve the viscous flow field around a cone at a zero angle of attack, after which they developed waveriders derived from the viscous basic flow field and studied them. They also compared two waveriders derived from the inviscid and viscous basic flow fields. A comparison of the rear views of these two waveriders is shown in Fig. 21. Because viscous flow can cause a slight increase in the shock wave angle, the thickness of the waverider derived from the viscous basic flow field was larger than that of the waverider derived from the inviscid basic flow field; however, this difference was fairly small, as shown in Fig. 21.

3. Design method and solving method of basic flow field

The design method of the basic flow field refers mainly to the calculation method of the flow parameters in the basic flow field, which depends on the type of basic flow field. In essence, the design of the basic flow field is the design of the waverider in the flow direction. The following are examples of the key design and solving methods of the basic flow field: an analytical method that involves solving of the oblique shock wave relation, the Taylor–Maccoll solution or hypersonic small-disturbance theory, the MOC, the space-marching finite difference method, the time-marching method for Euler equations (inviscid CFD method), and the time-marching method for Navier–Stokes (N–S) equations (viscous CFD method).

3.1. Analytical method that involves solving of oblique shock wave relation

The basic flow field for the wedge-derived waverider is a 2D plane flow past a wedge, and this kind of flow field can be solved rapidly and accurately by using the oblique shock wave relation.

3.2. Taylor–Maccoll solution or hypersonic small-disturbance theory

The basic flow field for the cone-derived waverider is a conical flow field around a cone at a zero angle of attack. This kind of flow field can be solved rapidly and accurately by solving the Taylor–Maccoll flow governing equations [46,47], which is an exact method; it can also be approximately solved by applying the hypersonic small-disturbance theory [48], which is an approximate method. Mangin et al. [49] from the CNRS performed a comparative analysis of the similarities and differences between cone-derived waveriders generated by both the exact method (solving of the Taylor–Maccoll flow governing equations) and the approximate method (application of the hypersonic small-disturbance theory). The analysis results indicated that there were no obvious differences between the lower-surface shapes of the two waverider configurations when the design Mach number was 5 and the cone half-angle was 5°; furthermore, for the same design Mach number and a cone half-angle of 12.9°, the lower-surface shapes of the two waverider configurations were very similar.

ICFA [27] is a kind of internal conical flow with a straight shock wave, and its governing equations are also the Taylor–Maccoll governing equations. In the design of the osculating internal cone waverider, He et al. [25] used a numerical method to solve the Taylor–Maccoll governing equations and then obtained the basic flow field.

With improvements in computational efficiency in recent times, the present-day Taylor–Maccoll solutions have all but supplanted the hypersonic small-disturbance theory. Furthermore, because of the ease of incorporation of the Taylor–Maccoll solution into a waverider design program, they have been employed extensively to solve the conical flow field.

3.3. MOC

The MOC is the most accurate numerical technique for solving hyperbolic partial differential equations [50]. This means that the MOC is applicable only to flow fields that are completely supersonic or hypersonic. Since the MOC was first applied to a supersonic flow problem by Prandtl and Busemann in 1929 [3], it has become a classical technique for solving inviscid supersonic or hypersonic flows of both the internal type and the external type. Even though the MOC methodology has been around since a long time, it is still extensively used in the design of modern hypersonic vehicles [3]. Goonko et al. [22] used the MOC to solve the internal conical flow field as the basic flow field in order to design a waverider. In the design of the curved-cone-derived waverider, He et al., [19,51] and He and Ni [51] solved the conical flow field by using the Taylor–Maccoll governing equations and used the calculated conical flow field as the initial line; they then used the MOC to solve the basic flow field around a curved cone at a zero angle of attack. When Sobieczky et al. [52,53] from the German Aerospace Research Center (DLR) applied the osculating axisymmetric theory for waverider design, they also used the MOC to solve the axisymmetric flow field in every osculating plane. You et al. [23] You [24], Yu et al. [54], and Huang et al. [55] all applied the MOC to rapidly calculate the basic flow field in the design of an internal waverider. Li et al. [56] also applied the MOC to calculate the external conical basic flow field with a controlled Mach number distribution and then used this basic flow field to design the waverider with controlled leading and trailing edges.

3.4. Space-marching finite difference method

The space-marching finite difference method, which has been widely applied since the early 1970s, is another exact solution of Euler equations, and it is also applicable only to flow fields that are completely supersonic or hypersonic; in this fashion, it is analogous to the MOC [3]. In the studies of Corda [17] and Corda and Anderson [57] on viscous optimized waveriders designed from axisymmetric flow fields, the space-marching finite difference method was used to generate the flow fields over minimum-drag bodies, especially a class of power-law bodies. As this method cannot be used for mixed subsonic-supersonic flow in the blunt-nose region, the blunt nose of the power-law body was modified to a pointed-cone nose. The Taylor–Maccoll solutions for the pointed-cone nose were used as the initial line for the space marching finite difference method.

3.5. Time-marching method for Euler equations (inviscid CFD method)

Because of the high efficiency and power of the time-marching method used to solve flows past blunt bodies or other nonaxisymmetric bodies, some researchers applied this method to solve Euler equations—which is known as the inviscid CFD method—and obtained a mixed subsonic-supersonic flow field or a nonaxisymmetric flow field as the basic flow field for the waverider design. In the optimization study of waveriders derived from axisymmetric power-law blunt body flows, Mangin et al. [16] applied the time-marching method to solve 2D axisymmetric Euler equations and obtained the basic flow fields past power-law bodies.

In order to verify the validity of using inviscid CFD to obtain the basic flow field for waverider design, Lobbia and Suzuki [58] from the University of Tokyo generated two waveriders from a conical flow field. The first waverider was designed using a basic flow field solved using inviscid CFD, and the second was designed using the Taylor–Maccoll solutions. Comparison results of these two waveriders showed that they had similar configurations and performance characteristics. However, the accuracy of shock capture in the inviscid CFD method was lower than that of shock fitting in the Taylor–Maccoll solutions, and numerical viscosity was present in the CFD algorithm; thus, the accuracy of the leading-edge location for waverider design as obtained using the inviscid CFD method was slightly lower than that using the Taylor–Maccoll solution. Subsequently, Lobbia and Suzuki [59] further experimentally validated their design method of the waverider derived from the basic flow field solved using inviscid CFD.

In the study of the wedge-cone-derived waverider and quasi-cone-derived waverider, Takashima and Lewis [38,39], and Cui and Yang [34], and Cui et al. [35] applied the time-marching method to solve 3D Euler equations and obtained the three-dimensional, nonaxisymmetric basic flow field around a wedge-cone body or a quasi-cone.

Inviscid CFD is an efficient tool for simulating 3D flow; however flow with a shock wave is complicated, especially in terms of the location of the shock wave, which is important for waverider design. The shock-capture method is often employed to locate the shock wave; however, nonphysical oscillation is present around the shock wave and the shock wave crosses several grids, and so, it is difficult to determine the initial point of streamline tracing. The shock-fitting method, on the other hand, can distinguish the shock wave easily and precisely, even though it may require more computational resources. With the aim of improving the resolution accuracy of a 3D shock wave and the accuracy of the leading-edge curve of a waverider, Liu et al. [36] employed the shock-fitting method to the 3D flow and captured the shock wave more precisely.

3.6. Time-marching method for N–S equations (viscous CFD method)

In their study of waveriders derived from the viscous basic flow field, Li et al. [43] applied the time-marching method to solve the N–S equations—which is known as the viscous CFD method—and obtained the viscous basic flow field for waverider design.

4. Osculating theory in spanwise direction

Given the simplicity and accuracy of the design method of the axisymmetric inviscid basic flow field, researchers have developed three types of design theories: osculating cone, osculating axisymmetric, and osculating flow field design theories. Based on the three osculating design theories, studies have been conducted on waverider design in the spanwise direction in order to obtain a series of new types of waveriders with higher design freedom and to meet specific design requirements.

4.1. Osculating cone design theory

The osculating cone design theory, which was first proposed by Sobieczky et al. [60] in 1990, is the first kind of spanwise design theory of a waverider. Its basic concept is as follows: the 3D flows designed by the osculating cone theory can be approximated locally by applying a conical flow in every osculating plane; in other words, a 3D flow with specific properties is constructed using conical flow, which is easy to solve, and specific properties of the constructed flow are obtained by the osculating cone theory. In detail, under the assumption that lateral flow is neglected or that lateral flow is too small to be considered, the 3D supersonic flow constructed by the osculating cone theory can be approximated with two-order accuracy by applying the conical flow in the local osculating plane; this greatly reduces the computational time of the 3D flow field used as the basic flow field of a waverider. Further, the design basis for the osculating cone waverider is the design of a 3D flow field according to the osculating cone theory. As a result of application of this theory, the shock-wave profile of the bottom cross section of the waverider is no longer limited to an arc or a straight line; instead, it can be rationally designed according to the shape of the inlet lip. Use of this theory greatly expands the design space and application range of the waverider.

Fig. 22(a) illustrates an osculating plane that is normal to the design shock-wave curve at point $P_{i,4}$, and Fig. 22(b) illustrates the conical flow field in an osculating plane. The design Mach number and shock wave angle, which define the locally conical flow, are required to be maintained constant in each osculating plane in order to prevent pressure gradients in the spanwise direction. The base radius of the locally conical flow equals the local curvature radius of the shock-wave curve. The vertex of the conical flow in each osculating plane is determined by the local curvature radius as well as the design shock-wave angle. The design shock-wave curve is chosen such that the variation in the curvature radius is continuous along the curve, and a series of osculating planes are constructed along the design shock-wave curve to fully define the flow field [61].

Chauffour in 2004 [62], Chauffour and Lewis in 2004 [63], and Lewis and Chauffour in 2005 [64]—all from the University of Maryland in the United States—modified the osculating cone theory by considering pressure gradient corrections in the spanwise direction. Their works validated the assumption that the azimuthal pressure gradients along the waverider are negligible at a sufficiently high Mach number (over Mach 4–5); however, with a minor modification, some modest improvement can be made in the prediction of the streamline location, albeit with a small decrease in the overall aerodynamic performance.

4.2. Osculating axisymmetric design theory

The osculating axisymmetric design theory is an extension of the osculating cone design theory developed by Sobieczky et al., [52,53] in 1997 and 1999. The 3D flows designed by the osculating axisymmetric theory can be approximated locally by applying a type of axisymmetric flow in each osculating plane. In other words, the basic flow field in the osculating plane is no longer limited to the conical flow; rather it is an appropriate axisymmetric flow field that meets design requirements. The basic flow field in each osculating plane can be scaled by the same axisymmetric basic flow field model, and the scaling ratio is determined by the curvature radius of the shock-wave profile of the bottom cross section of the waverider.

Wang and Qian [65] from the Beijing University of Aeronautics and Astronautics performed a comparison study of three types of waveriders: those derived using the conical flow field theory, osculating cone design theory, and osculating axisymmetric design theory. Their study results showed that the design method of using the conical flow field theory is relatively simple and it provides a high lift-to-drag ratio, but the inlet flow field is not quite uniform; thus, this approach is not beneficial for the engine. In contrast, application of both the osculating cone design theory and the osculating axisymmetric design theory can give waveriders that are more universal and improve the inlet flow field quality. Additionally, all three design methods have a high computational speed, which is quite promising for the subsequent integration design and optimization process.

In the study of He et al. [19], they used, in each osculating plane, a curved conical flow around a concave curved cone consisting of a straight shock wave along with a group of isentropic compression waves as the basic flow field and developed an osculating curved-cone-derived waverider. They then verified this waverider design method via numerical simulation [19] and subsequently compared and analyzed both the osculating curved-cone-derived waverider and the osculating cone-derived waverider. The study showed that the osculating curved-cone-derived waverider successfully overcomes the shortcoming of insufficient compression of air flow at the exit cross section of the waverider and also provides an obviously improved volumetric efficiency in comparison to the osculating cone-derived waverider.

4.3. Osculating flow field design theory

The osculating flow field design theory was first proposed by Rodi [66–69] from the American Lockheed Martin Corporation. It is an extension of the osculating cone and osculating axisymmetric design theories: the basic flow field in each osculating plane is no longer confined to the same axisymmetric flow field; rather, different axisymmetric flow fields can be chosen in each osculating plane according to the design requirements.

A preliminary study [66] showed that the waveriders derived from the osculating flow field theory have the following advantages over those derived from the osculating cone theory: (1) reduced trim drag through an improved streamwise lift distribution, (2) an increased vehicle volume for a given aerodynamic performance, (3) a forward shift in the center of mass position, (4) reduced viscous drag through delayed boundary-layer transition, and (5) an improved aft body close-out geometry.

A further study [67] showed that for a given volumetric efficiency under a design Mach number of 16.0, the waverider derived from the osculating flow field theory shows up to a 7% increase in the inviscid lift-to-drag ratio over the waverider derived from the osculating cone theory, and this increase percentage improves with a decrease in the waverider's design Mach number.

Unlike Rodi's osculating flow field theory, which is limited to the basic flow field with an external compression shock wave, a new osculating flow field theory, developed by You et al. [70] from the Nanjing University of Aeronautics and Astronautics, can combine the basic flow field with an external compression shock wave with that with an internal

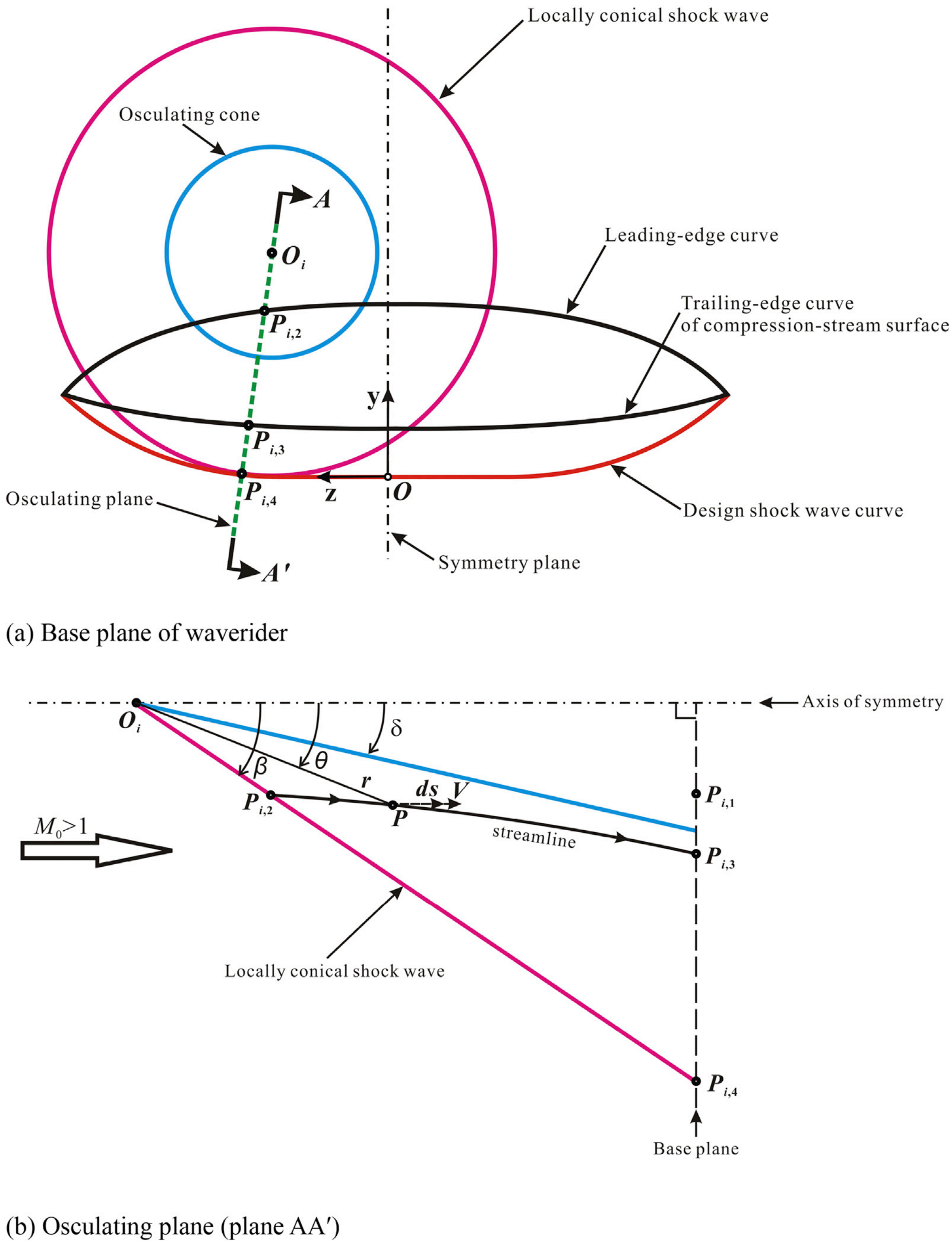


Fig. 22. Schematic illustration of osculating cone theory [61].

contraction shock wave; this new theory was termed the dual waverider design concept. Through design of a unique lip shock wave with a continuously changing curvature in the spanwise direction, the basic flow field in the osculating plane can be continuously transferred from the internal contraction shock wave on the forebody's inner side to the external compression shock wave on the forebody's outer side. Thus, two completely different basic flow fields—the inner-side basic flow field with an internal contraction shock wave and the outer-side basic flow field with an external compression shock wave—are closely and effectively combined. The internal contraction shock wave can be used to design the internal waverider as the precompression surface to provide high-efficiency compression air flow for the engine, and the external compression shock wave can be used to design the external waverider as the lift surface to provide a high lift-to-drag ratio for the airframe; the internal waverider and the external waverider together constitute the dual waverider. As shown in Fig. 23, at any cross section before the lip, the forebody's inner side rides on the internal contraction shock wave, i.e., the internal waverider, and the forebody's outer side rides on the external compression shock wave, i.e., the external waverider.

The design concept of the dual waverider has greatly expanded the scope of the osculating flow field design theory. Although the volumetric efficiency and lift-to-drag ratio of the dual-waverider configuration are still worthy of examination and study, it is an ideal design method for the concept of combined internal and external waveriders.

5. Waverider remodel design

With the aim of improving the aerodynamic performance of the

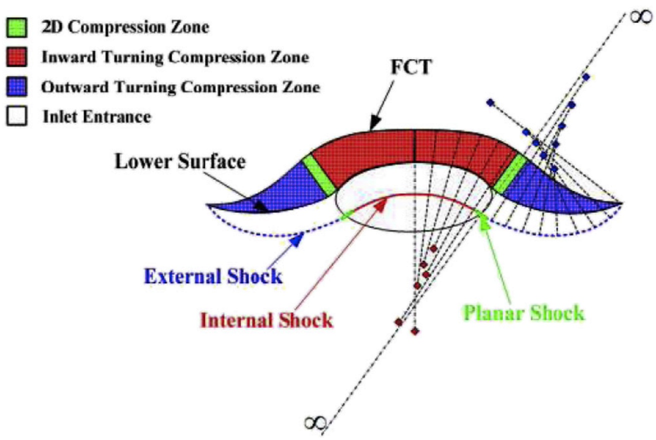


Fig. 23. Schematic representation of dual waverider [70].

waverider for some special tasks, some researchers have designed various kinds of waveriders and proposed several new design methods of waveriders.

5.1. *Combination design of wide-speed-range waverider*

In order to improve the waverider's overall aerodynamic performance in the full range of subsonic, transonic, supersonic, and hypersonic speeds, in 2009, Wang et al., [71,72] from the Chinese Academy of Sciences proposed the design concept of a combination of a high-speed waverider and a low-speed waverider. As shown in Fig. 24, this kind of wide-speed-range waverider is composed of a high-Mach-number waverider (high-Mach waverider for short) and a low-Mach-number waverider (low-Mach waverider for short), and the high-Mach waverider is placed before the low-Mach waverider; both these waveriders are connected through a connecting section. The front section of the wide-speed-range waverider, i.e., the high-Mach waverider, can ride on the shock wave at the design high Mach number, and the rear section of the wide-speed-range waverider, i.e., the low-Mach waverider, can ride on the shock wave at the design low Mach number; as a result, the wide-speed-range waverider can maintain a good aerodynamic performance over the entire flight envelope.

Li et al., [73,74] from the National University of Defense Technology referred to the combination design concept of Wang et al., [71,72] and developed two types of combination design methods for the wide-speed-range waverider. They used two design ideas to improve the aerodynamic performance over a wide range of Mach numbers (4–8). One is the design idea for a tandem waverider: the wide-speed-range waverider is constructed by combining two waveriders generated from different design Mach numbers in tandem. As shown in Fig. 25, similar to the theory of Wang et al. as shown in Fig. 24, the high-Mach waverider is placed before the low-Mach waverider and both these waveriders are connected through a connecting section. The other is the design idea for a parallel waverider: a series of waveriders generated from different design Mach numbers are combined in parallel according to a certain rule, and a combined wide-speed-range waverider is obtained (see Fig. 26).

Although the waveriders generated by the three combination design methods described above do not strictly possess the characteristics of a waverider riding on a shock wave, they are also a valuable engineering application attempt in the field of waverider design.

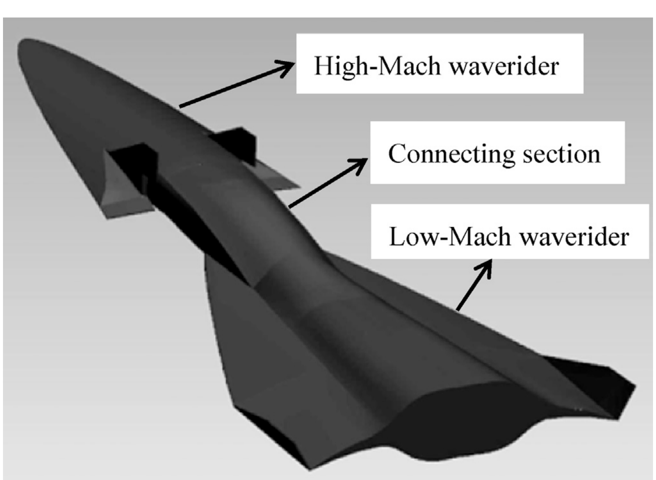


Fig. 24. Wide-speed-range waverider [71].

5.2. *Gliding–cruising dual waverider design*

With the aim of researching a combined hypersonic unpowered gliding and powered cruising vehicle and for obtaining a deformation waverider configuration with a high lift-to-drag ratio in both a high-Mach-number gliding phase and a low-Mach-number cruising phase, Liu and Ding et al. [1] from the National University of Defense Technology proposed a new design concept, namely, a gliding–cruising dual waverider, as shown in Fig. 27. They generated a gliding–cruising dual waverider derived from a conical flow field; its geometric model is shown in Fig. 28.

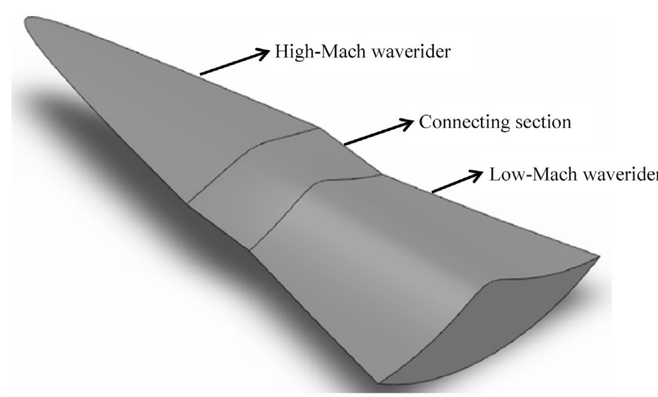


Fig. 25. Wide-speed-range tandem waverider [73].

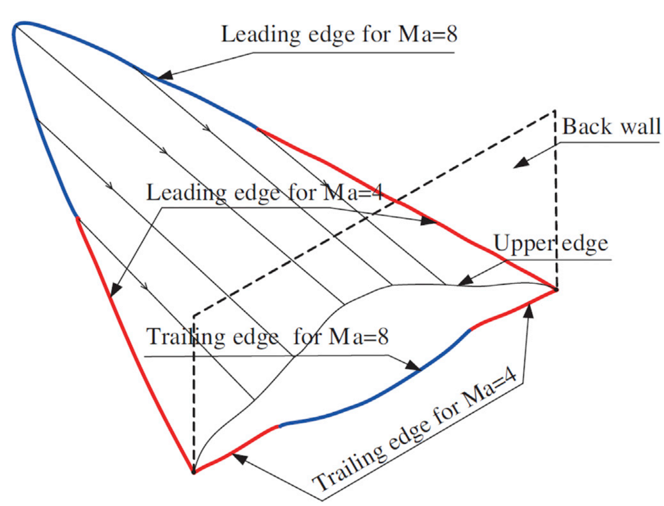


Fig. 26. Wide-speed-range parallel waverider [74].

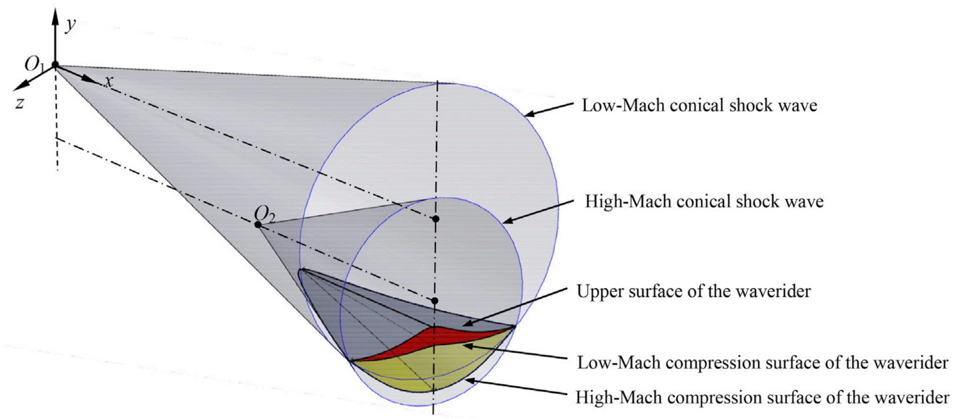


Fig. 27. Basic design principle of gliding–cruising dual waverider derived from conical flow field [1].

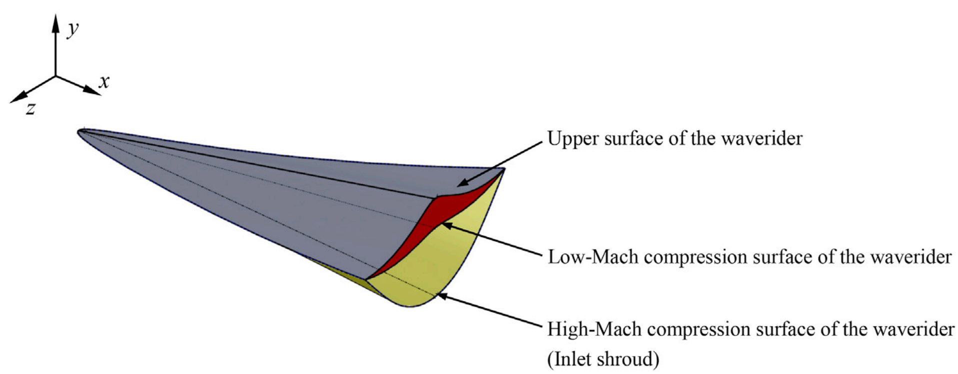


Fig. 28. Geometric model of gliding–cruising dual waverider derived from conical flow field [1].

As shown in Fig. 27, the design concept of the gliding–cruising dual waverider is as follows: during the gliding phase, the hypersonic vehicle rides on the shock wave at the design gliding Mach number, as the inlet shroud is designed to act as the waverider's compression surface; during the cruising phase, when the inlet shroud is cast away or jettisoned, the hypersonic vehicle rides on the shock wave at the design cruising Mach number, as the forebody is also designed to act as the waverider's compression surface. Thus, the gliding–cruising dual waverider has a higher average lift-to-drag ratio throughout the entire flight, and this can extend the range of the vehicle significantly.

Subsequently, the design theory of the gliding–cruising dual waverider was extended by Wang [75], and the design theory and design method of a gliding–cruising dual waverider derived from the osculating cone were studied. On the basis of this study, the osculating cone theory with a variable shock wave angle was further developed, and the gliding–cruising dual waverider based on this theory was extended. Its configuration is shown in Fig. 29.

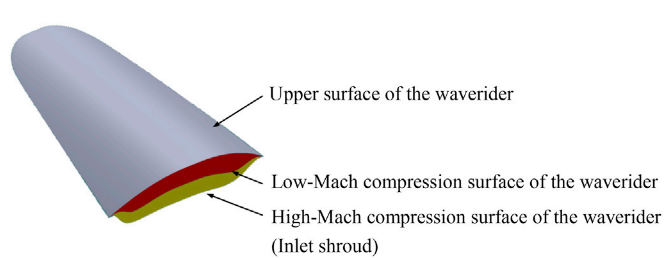


Fig. 29. Geometric model of gliding–cruising dual waverider derived from osculating cone theory with variable shock wave angle [75].

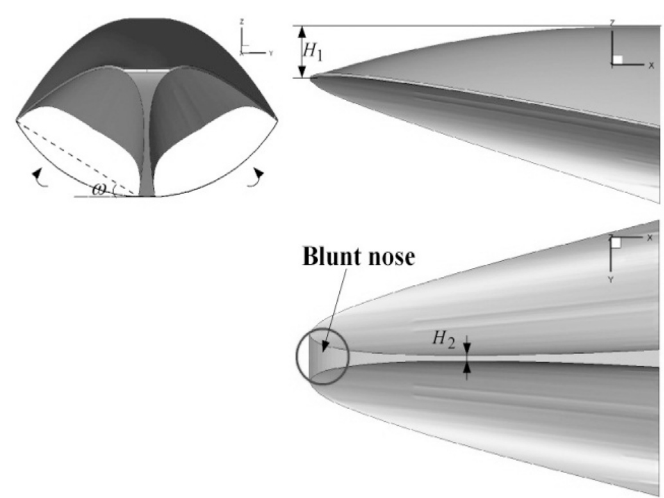


Fig. 30. Double waverider forebody [76].

5.3. Double waverider forebody design

In order to meet the design requirements of a high lift-to-drag ratio and high volumetric efficiency of a hypersonic airplane, a kind of hypersonic airplane configuration with double flanking air inlets was proposed by Cui et al., [76,77] from the Chinese Academy of Sciences, and the design method of a double waverider forebody, which entailed rotation and assembling of two waverider-based surfaces, was first introduced. The geometric model of the double waverider forebody is shown in Fig. 30. It is worth noting that the double waverider concept of

Cui et al. [76,77] differs from the above-described dual waverider concept of You et al. [70]. The former concept is that both the left and right sides of the forebody ride on the shock wave; the latter concept is that the forebody's inner side rides on the internal contraction shock wave, i.e., the internal waverider, and the forebody's outer side rides on the external compression shock wave, i.e., the external waverider, and the internal waverider and external waverider together constitute the dual waverider.

5.4. Star-shaped body or star-body waverider

Ostapenko and Zubin et al. [78–83] from the Sussian Moscow State University combined several V-shaped wings (i.e. "Λ" waveriders) along the circumference and designed a pyramidal body with a star-shaped cross-section, which is termed the star-shaped body. The star-shaped body with four petals (i.e. four V-shaped wings) are shown in Fig. 31. Both the theoretical and experimental results indicated that the star-shaped body has a much lower wave drag than the body of revolution of the equivalent length and midsection area [81,84]. The marked reduction of the wave drag is explained physically by the formation of a system of weak shocks which arise from the star-shaped body in place of the strong axisymmetric wave which arises from the body of revolution [86]. Thus, the star-shaped bodies can be regarded as promising supersonic and hypersonic flight vehicles because of the low drag and high lift-to-drag ratio [80].

Moreover, in 2009, Corda [87] from the University of Tennessee Space Institute combined four wedge-derived waveriders ("Λ" waveriders) along the circumference and designed a star-shaped configuration termed the star-body waverider, as shown in Fig. 32. He also pointed out that the design Mach number of the four waveriders distributed along the circumference of the star-body waverider can be 1, 2, or 3, corresponding to the axisymmetric configuration, plane symmetry configuration, and nonsymmetric configuration, respectively. Rodi [88] further studied the application of the nonsymmetric star-body waverider to the generation of pitching, yawing, and rolling moments from a nonsymmetric surface pressure distribution.

5.5. Multistage compression waverider

In order to further improve the waverider's ability to precompress air flow, a design method of a multistage compression waverider was developed by Lyu and Wang [89], Lyu et al. [90,91], and Wang et al. [92], from the Nanjing University of Aeronautics and Astronautics, in 2015 and 2016. According to the conical flow field theory and osculating cone design theory, a waverider configuration with multiple compression ramps was obtained by the streamline tracing method. The basic flow field with three-stage compression ramps used in Lyu and Wang's waverider design [89] is shown in Fig. 33, and the designed three-stage compression cone-derived waverider and three-stage compression osculating-cone-derived waverider are shown in Fig. 34(a) and (b), respectively. The basic flow field with two-stage compression ramps used

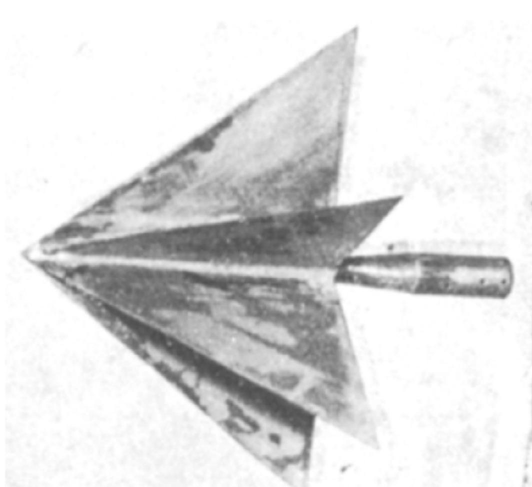


Fig. 31. Star-shaped body with four petals [85].

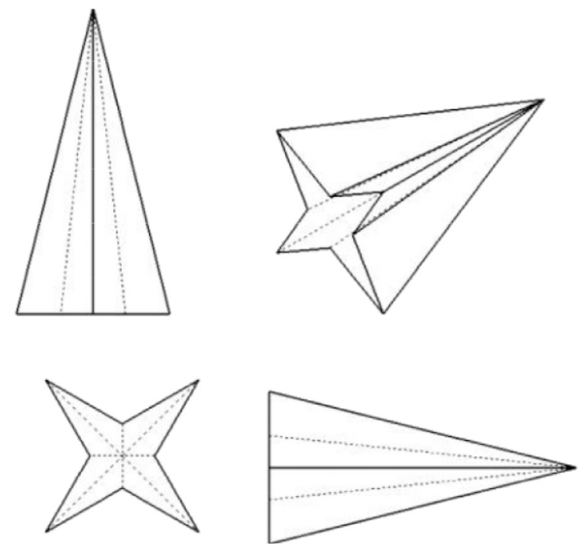


Fig. 32. Star-body waverider [87].

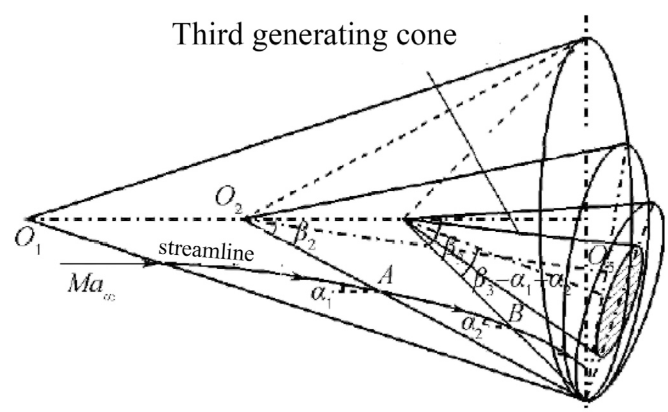


Fig. 33. Schematic illustration of basic flow field of multistage compression waverider with three-stage compression ramps [89].

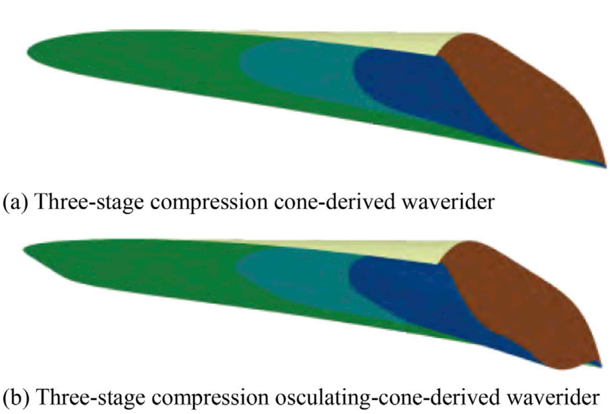


Fig. 34. Geometric models of three-stage compression cone-derived waverider and three-stage compression osculating-cone-derived waverider [89].

in the design and study of the multistage compression waverider by Wang et al. [92] is shown in Fig. 35.

5.6. Other waverider designs

To meet the design requirements of large capacity, high lift, low drag, and high lift-to-drag ratio for high-speed aircraft, the concept of a high pressure zone capture wing (HCW), shown in Fig. 36, was proposed in 2014 by Cui et al. [93] from the Chinese Academy of Sciences. Under high-speed cruise conditions, the vehicle configuration enables the HCW to make full use of the high-pressure air of the inflow to improve the vehicle's lift. Moreover, the HCW is a thin plate device parallel to the inflow, the additional drag generated by the HCW is small, and the lift-to-drag ratio can be improved greatly. In a sense, the HCW is a kind of application of the waverider concept.

In order to improve the lift-to-drag ratio in the landing phase, a practical waverider with outer wings as shown in Fig. 37 was proposed in 2011 by Takama [94] from the Japan Aerospace Exploration Agency. The study results showed that the outer wings attached on the waverider can increase the lift-to-drag ratio in the subsonic regime but these wings have little effect on the hypersonic characteristics. The proposed practical waverider successfully showed improved low-speed performance without any degradation in the high hypersonic performance, which was an original advantage of the waverider. Thus, this design concept can be applied to the design of wide-speed-range vehicles.

6. Conclusions: development trend of waverider design methods

The following trends can be identified from a review of developments of waverider design methods made by local and foreign scholars.

(1) The general concept of the waverider design method is to design a waverider in the flow direction through design of the basic flow

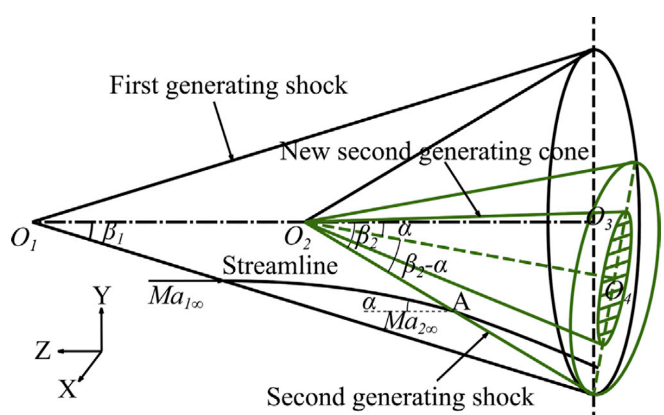


Fig. 35. Schematic illustration of basic flow field of multistage compression waverider with two-stage compression ramps [92].

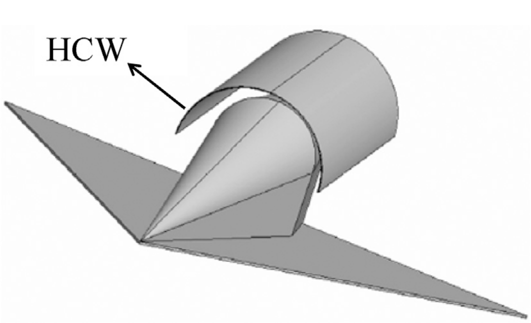


Fig. 36. Concept of high pressure zone capture wing (HCW) [93].

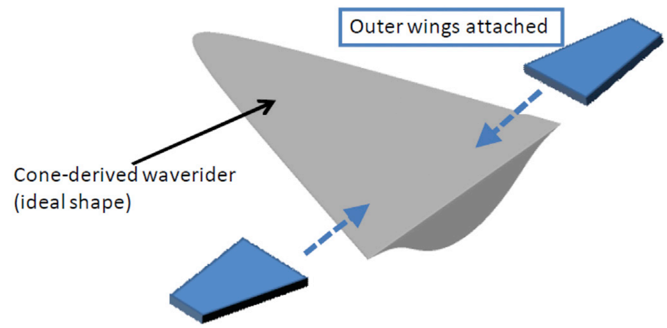


Fig. 37. Practical waverider with outer wings [94].

field and to apply the osculating cone theory to design the waverider in the spanwise direction.

(2) The basic flow field for the design of the waverider is no longer confined to a conical flow field with a straight shock wave but is instead further extended to an axisymmetric flow field with a curved shock wave. Through application of the osculating axisymmetric design theory and the osculating flow field design theory, the basic flow field can be extended to a more complicated, 3D nonaxisymmetric flow field.

(3) The development of a more general basic flow field provides a wider design space and more design concepts for waverider design. In engineering applications, a more advanced osculating theory is adopted to provide a uniform flow field for the inlet and to achieve a tradeoff between the lift-to-drag ratio and the volumetric efficiency, and this will potentially result in a more practical waverider.

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