Study on the Current Status and Development Direction of Hypersonic Vehicle Research

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Abstract. Hypersonic vehicle has important scientific research value and application prospect. The aerodynamic layout structure to cope with the complex flow characteristics in the high-speed environment is the core factor affecting the performance of hypersonic vehicles. Until now, the design and development process of hypersonic vehicles still faces great challenges. At present, the commonly used aerodynamic layout structures include lift body, wave multiplier and so on. Among them, the Waverider body aerodynamic layout has a higher lift and lift-to-drag ratio, which is also a development direction for future hypersonic vehicles. This paper reviews the research progress of various countries in the field of hypersonic vehicles, analyzes and summarizes the main characteristics of different aerodynamic layout vehicles, and looks forward to the future development direction of hypersonic vehicles in military and civil fields. The future development direction of hypersonic vehicles in civil field is prospected.

Keywords: hypersonic, lifting body, Waverider, aerodynamic layout

1 Introduction

In recent years, with the rapid development of artificial intelligence and autonomous system technology, the research focus of hypersonic vehicle is changing from traditional platform design to intelligent and autonomous collaborative control. The core challenge is how to achieve a "perception-decision-control" closed loop similar to high-level intelligent driving under extreme flight conditions. This requires the aircraft not only to withstand harsh aerodynamic and thermal environments, but also to sense real-time states through multi-source sensor fusion, to make safe and efficient flight decisions in milliseconds through intelligent algorithms, and to respond autonomously to complex disturbances. Therefore, hypersonic vehicle aerodynamic configuration, thermal protection and control system design must be deeply coupled with advanced unmanned technology to support its fully autonomous flight capability in high dynamic environments [1].

The intelligent development of hypersonic vehicle depends on the breakthrough of three key technologies: intelligent navigation and control, advanced thermal protection system (TPS) and green propulsion technology. First of all, the aircraft navigation in extreme dynamic environment surpasses the traditional inertial/satellite combination

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mode, and artificial intelligence (AI) algorithm needs to be introduced for multi-source sensor fusion and real-time decision-making to cope with challenges such as "black barrier" communication interruption. Secondly, the ultra-high temperature environment caused by aerodynamic thermal effect requires thermal protection systems not only to have excellent heat resistance, but also to be combined with smart materials to achieve active thermal management of "perception-response" integration. Finally, in order to meet the needs of sustainable aviation, the application of new green propulsion technologies such as detonation combustion and cryogenic propellants is becoming a research hotspot [2]. This paper will summarize the evolution path of hypersonic vehicle from "capable flight" to "good flight" and "intelligent flight" around these three directions.

Hypersonic vehicles play an equally important role in aerospace. Hypersonic vehicles can fly at Mach speeds both in and out of the atmosphere, which requires high stability and energy conversion efficiency of the vehicle itself.

The main aerodynamic configurations of hypersonic vehicles include waverider, lifting, spin and wing-body fusion. In the middle of the last century, researchers discovered strong aerodynamic interference between wings and fuselage and tried to adopt aerodynamic configurations in which the fuselage could also provide some of the lift needed for flight [3]. In 1922, the predecessor of the lifting body aircraft RB.2h [4] was successfully developed. The RB.2h is an aircraft with a wing-shaped fuselage. In 1947, Canada developed the CYB-3 aircraft. In 1962, NASA engineer Reed conducted research related to lifting body design, producing several glider models of lifting body structures that initially confirmed the feasibility of lifting body aerodynamic configuration concepts; from 1963 to 1975, NASA conducted lifting body aircraft research projects, examining M2.F1, M2.F2, M2.F3, HL-10, X-24A F2, M2.F3, HL-10, X-24A, and X-24B, including some that had successfully flown. Although these original vehicles performed poorly and could not be put to final use, they provided the basis and reference value for later American lift-body spacecraft and space shuttles. Over the past decade or so, with rapid advances in aerospace technology, interest in lifting-body structures has revived, and NASA Langley Research Center, U.S. programs, and Boeing have conducted extensive research on lifting-body shaped aircraft. In the "Into Space" program, the United States has successfully launched HL-20, X-33 and X-38 launch vehicles into space. These hypersonic vehicles were tested in experiments and eventually put into service. The X-33 [5] aircraft, which was a wedge or delta wingless design, completed its test mission at Edwards at speeds up to Mach 7, as shown in Figure 1; Developed jointly by the Drayton Flight Research Center (DFRC) and Johnson Space Center (JSC), the X-38 has unpowered glide and can be used as a manned return spacecraft. Both the X-33 and X-38 are reusable aircraft. Aerodynamic configurations of lifting bodies are currently used on some United States space shuttles.

Fig. 1. American X-33 aircraft.

Waverider was proposed during Queen's College's Blue Stripe manned space program in the 1950s. Then, in 1959, Nonweiler [6], head of the Department of Aeronautics and Engineering, first introduced the concept of wave multipliers at the University of Glasgow.

Hypersonic vehicle design and manufacture is an extremely complex system engineering, involving aerodynamics, computational fluid dynamics, material science and structural design. Among them, aerodynamic characteristics are the main factors affecting the performance of hypersonic vehicles. This paper describes the development process, theoretical basis, application and future development trend of the two most common aerodynamic configurations of hypersonic vehicles [4].

Before delving into the details of the aerodynamic configuration of lifting bodies and Waveriders, it is crucial to outline their development timelines. The lifting body concept was first proposed in 1957 and made significant progress through NASA research between 1963 and 1975, leading to successful test flights of aircraft such as the X-33 and X-38. The Waverider concept was introduced in 1959, became prominent with the development of military missiles, and was prominently displayed in the X-51A cruise missile in 2010.

These groundbreaking theoretical work laid the aerodynamic foundation for hypersonic flight. However, to turn concepts into reality, extreme environmental challenges in engineering practice must be addressed, which has pushed the world's major space agencies into a large-scale technology demonstration phase [5].

2 Lifting Body

The lift body concept was originally proposed by Eggers Jr in 1957 [7]. In the early days of the founding of the United States, the cost of spacecraft recycling was huge, and there was an urgent need for a more cost-effective, time-saving and reusable spacecraft. In 1962, NASA engineer Reed started to research on this type of vehicle and developed it successfully in 1963. Compared to conventional vehicles, the lifting body has less overall drag when flying, which comes from its wing and fuselage fusion design. It is provided with lift by the fuselage itself. The upper layer of the fuselage has a fast gas flow rate and low gas pressure. In the lower part of the fuselage, the curved raised structure produces a certain resistance, so that the gas flow rate is slower, the lower gas produced a higher air pressure, the vehicle in this pressure difference gained lift. In high-speed flight, it can generate enough lift [6]. In addition, the vehicle also has the advantages of light weight, ruggedness, versatility and maneuverability. When returning to the atmosphere, conventional vehicles are often unable to withstand the high temperatures generated by the high-speed airflow against their own drag, making it difficult to ensure stability and even risk disintegration. For the lifting body without wings, its advantages can be reflected. It can obtain a higher lift-to-drag ratio at a lower flight speed.

However, the lifting body aircraft was not widely recognized at first. People first talked about its appearance, and it was nicknamed "Big Fat Man". NSAS also did not support the related research and development projects based on more funds. Even so, the lifting body aircraft completed the relevant test verification work.

2.1 X-33 Aircraft

In 1999, NASA entered into an agreement with Lockheed Martin to begin designing and manufacturing the X-33 high-tech flight test demonstrator, a lifting body aircraft. The lifting body vehicle is powered by a new Aerospike rocket engine and has a sturdy metal heat shield over its body. This is also part of the reusable launch vehicle (RLV) program. The X-33 is an unmanned aerial vehicle that can launch vertically like a rocket and land horizontally like an airplane. It flies at an altitude of about 50 miles and speeds of Mach 11 or higher. To achieve higher lift-to-drag ratios, the X-33 adopted a hyperboloid design on the windward side and seven control surfaces for safe and stable lateral and longitudinal control.; The ailerons and dihedral wings on either side of the fuselage are used to control roll, yaw and provide lift for flight, while the elevator and rudder on the lower surface of the fuselage and a pair of elevons are used to control pitch and roll.

Service of the X-33 reduced the cost of putting payloads into space from $10,000 per pound to $1,000, resulting in significant savings in launch costs. However, in 2001 NASA stopped funding the project.[5] During the program period, more than 600 aerodynamic tests, more than 1100 thermal tests, and more than 4000 engine ignition tests were performed, and a large amount of numerical data was supplemented by relevant numerical calculations (CFD) to form a database of X-33 overall and local performance characteristics, laying a solid foundation for future hypersonic vehicle development [7];

The X-33 uses advanced thermal protection materials and structural design to effectively resist high temperature erosion during high speed flight. X-33 is coated with special thermal protection material, which has excellent thermal insulation and high temperature resistance. This material can maintain stability in high temperature environments and prevent heat conduction to the internal structure of the vehicle. This material can not only withstand the high temperature generated during hypersonic flight, but also maintain good mechanical properties in complex aerodynamic environments to ensure the structural integrity and safety of the aircraft [8].

The X-33 design team adopted innovative thermal protection structural designs. The vehicle surface adopts multi-layer thermal insulation structure, and each layer of material has different thermal conductivity and thermal insulation effect. This multi-layer structure can effectively disperse and absorb heat, reducing the impact of heat on the interior of the vehicle. The X-33 also incorporates advanced cooling technology. By arranging cooling channels on the surface of the vehicle, the excess heat is taken away by coolant circulation, and the surface temperature of the vehicle is further reduced.

The X-33 's thermal protection technology was innovative not only in materials and structural design, but also in system integration and testing.; Through ground and flight tests, the X-33 's thermal protection system has been fully validated, demonstrating its reliability and effectiveness in hypersonic flight environments.; These advanced thermal protection technologies provide a solid foundation for the successful flight of the X-33 vehicle and valuable experience for the development of future hypersonic vehicles.

X-33 's thermal management technology has inspired future research on smart materials. At present, self-healing ceramic matrix composites are hot topics. When microcracks appear, the material can automatically fill the cracks at high temperatures through built-in repair agents, restoring structural integrity. In addition, piezoelectric fiber composites are used for active vibration control to suppress chatter and reduce local overheating due to vibration by applying reverse electric fields in real time. These smart materials, combined with embedded sensor networks, form a sense-analyze-respond intelligent thermal protection system, the core of which is to transform thermal protection from static passive to dynamic active management.

2.2 HIFiRE-5 Aircraft

Following the X-33, the international cooperative HIFiRE-5 project represents a new phase in hypersonic technology demonstration. HIFiRE-5 is a hypersonic flight test program supported by the Hypersonic International Flight Research Experiment (HIFiRE) [9] project and studied by AFRL and DSTO in cooperation [10]. The program involves numerous aspects, including aerodynamics, propulsion systems, navigation, control, and materials, among others.

HIFiRE-5 focuses more on hypersonic flight technology, which can further increase the flight speed and flight radius at a lower flight cost. From HIFiRE-1 to HIFiRE-5, researchers have conducted numerous experimental studies, focusing on the effects of boundary layer transitions on vehicle aerodynamic performance at high speeds. HIFiRE-2 is the predecessor of HIFiRE-5, as shown in Fig.3. During the flight test, it was transported to an altitude of about 100,000 feet by means of a rocket, and then separated from the rocket. The speed was accelerated from Mach 6 to Mach 8, and it continued to run for 12 seconds. The modal transition test was successfully completed, which was a great progress in the field of hypersonic flight.

HIFIRE-5 [8] is an elliptical cone, shown in Figure 2, which was flight tested in April 2012. However, due to the failure of the second stage booster, the flight altitude was only 50 km, far lower than the expected 300 km. During its ascent, it has a maximum velocity of slightly more than 900 m/s. During descent at Mach 2.4-2.7, the vehicle's leading edge exhibited a bypass turn, in good agreement with previously conducted wind tunnel tests.

The HIFiRE-5 aircraft is a key component of the hypersonic flight test program to explore hypersonic flight technology. In terms of aerodynamic configuration, HIFiRE-5 adopts a unique shape design to adapt to the aerodynamic characteristics of hypersonic flight. Its shape is designed to reduce drag and increase lift-to-drag ratio, thereby increasing flight efficiency. At the same time, the design also ensures that the aerodynamic performance of the aircraft in different flight phases is balanced, so that it maintains good flight attitude and control performance during acceleration, cruise and deceleration.

In terms of material selection, HIFiRE-5 faces the challenge of high temperature and high stress. The R & D team selected a variety of high-performance materials. These materials are not only resistant to heat, but also able to withstand various stresses during flight, ensuring the structural strength and safety of the aircraft. In addition, in order to reduce weight, the team also focused on lightweight design of materials to improve the payload capacity and flight speed of the aircraft.

In terms of system integration, HIFiRE-5 integrates multiple complex systems internally, including propulsion systems, AI-enhanced navigation and control systems, communications systems, and test payloads. Unlike earlier aircraft, its navigation system uses INS/GNSS/CNS deep fusion algorithms based on Robust Untraceable Kalman Filter (RUKF)(Hu et al., 2023) to cope with high dynamics and possible signal interruptions. The R & D team organically integrates these systems through advanced design concepts, aiming to achieve a certain degree of autonomous decision-making and flight management, providing a verification platform for the application of intelligent driving technology under hypersonic conditions. The R & D team organically integrates these systems through advanced design concepts to achieve efficient collaborative work. High-performance engines provide sufficient thrust for the aircraft, while navigation and control systems ensure that the aircraft flies steadily along a predetermined trajectory. The communication system ensures the transmission of information between the aircraft and the ground control center, and the test payload is used to obtain high-quality test data. The core of system integration of modern hypersonic vehicle is to construct a robust and intelligent vehicle-environment interaction system similar to unmanned vehicle. This goes beyond traditional flight control systems and integrates multi-modal environment-aware sensor networks (such as optical, infrared, radar), high-performance edge computing units (for real-time processing of sensor data and running intelligent algorithms), and autonomous mission planning and decision modules. For example, in the process of high-speed reentry or cruise, the aircraft needs to construct the situation portrait in the flight corridor in real time through sensor fusion technology, and dynamically optimize the flight trajectory and attitude through deep reinforcement learning algorithm according to preset mission objectives and real-time constraints (such as thermal load and structural stress), so as to realize the comprehensive optimization of energy, thermal management and aerodynamic performance, and show highly autonomous intelligent driving characteristics.

During the test, HIFiRE-5 successfully completed most of the test tasks and obtained valuable flight data. The project represented by HIFiRE-5 promotes the intelligent navigation algorithm from theory to practice. For example, multisensor fusion techniques based on deep learning can effectively deal with the cumulative errors of inertial navigation systems (INS) and signal loss problems of global navigation satellite systems (GNSS). Specifically, Long Short Term Memory Networks (LSTM) are used to model and predict INS errors, while Convolutional Neural Networks (CNN) are used to match visible/infrared images in real time to aid astronomical navigation (CNS). This AI-enhanced navigation system can control the positioning error within an acceptable range even under extreme conditions, providing a reliable state-aware basis for autonomous decision-making of aircraft.

Projects such as X-33 and HIFiRE successfully verified the feasibility of core technologies, but also exposed the great difficulty of achieving stable control in complex environments. This heralds the next frontier in hypersonic research: upgrading the vehicle from a mechanical platform that requires fine control to an intelligent system with environmental awareness and autonomous decision-making capabilities.

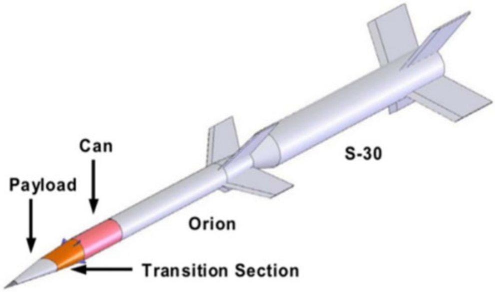

Fig. 2. Structural layout of HIFiRE-5 [10].

3 Waverider

3.1 Development History

A waverider will produce shock waves during flight. A shock wave is a strong compression wave. During shock formation, the aerodynamic parameters change abruptly. After surge occurs, the pressure, temperature and density of the air increase significantly, while the velocity of the air suddenly decreases. The waverider can exhibit good "waverider" characteristics when flying at hypersonic speed. The front plane of the fuselage coincides with the upper surface of the surge wave, just like riding on the wave, and generates lift by pressure difference. Compared with other models, it has the characteristics of high lift-drag ratio. In 1989, at an international conference on waverider aircraft sponsored by NASA at the University of Maryland, Sobieczky [11] and others proposed a method for forming tangent cones. In 1990, the design theory of osculating cone was put forward, and the excitation waveform was represented by arc, and the complex excitation surface was constructed by cone flow field, which expanded the application range of waverider.

Figure 3 systematically shows the integrated design of scramjet engine: bow shock wave is generated by forebody to pre-compress high-speed incoming flow; secondary compression of air is realized by shock layer interaction in inlet passage; shock train is used to stabilize flow field in isolation section to prevent high-pressure gas backflow in combustor; fuel injection technology is adopted in fuel subsystem to ensure sufficient mixing of fuel in supersonic flow; A stable supersonic flame is formed in the combustor, and the high temperature gas accelerates through the inner nozzle to generate effective thrust with the afterbody configuration. In Figure 3, the coupled control of shock systems and combustion is particularly emphasized: shock compression of the precursor/inlet will raise air temperatures to 2000 K, while constant volume combustion in the combustor will raise gas temperatures above 3000 K. Through asymmetric expansion design, the nozzle can reduce heat load and increase specific impulse by 15%-20%. This design scheme has been applied to X-51A waverider vehicle and 210 s continuous hypersonic combustion has been successfully achieved.

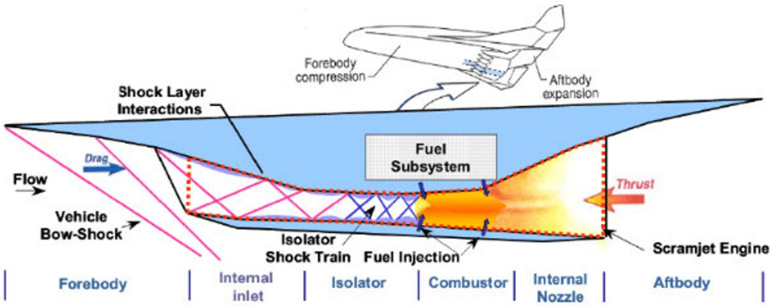

Fig. 3. Schematic diagram of scramjet engine structure

The X-51A program has a long history, dating back to the X-30 Space Shuttle National Aviation Safety Program (NASP) program from 1982 to 1985. The scramjet engine was proposed as a power plant in the early days of the project, but the thrust generated by the engine was offset by air drag and heat from the hot gases, and the maximum flight Mach number was only Mach 8, which was about 1/3 of the expected Mach 25. If super-internal combustion engines are used as power sources, booster rockets are needed, which makes the aircraft larger and more complex. Supported by the NASP project, researchers have discovered a way to achieve higher speeds for aircraft through thermal management-cyclic heating of hydrogen propellants.

On May 26, 2010, the United States flew the X-51A, a hypersonic cruise missile test vehicle. The X-51A uses a hypersonic ramjet engine as propulsion. The flight test verified the principle of scramjet engine and the feasibility of aerodynamic layout of waverider, which indicated that the core technology of hypersonic cruise missile was about to mature. The scramjet, developed by Pratt & Whitney, burned successfully for 200 seconds, accelerating the X-51A to Mach 5, breaking the previous record set by NASA's X-43. Project officials called the experiment an indisputable success. It was the first jet aircraft to use hydrocarbon fuel in flight. In the next test, the X-51A was flown aboard the B-52 Stratosphere Woman, as shown in Figure 4, launched from Project Edwards, California, and released at an altitude of 50,000 feet above the Naval Air Combat Center Sea Range at Cape Mugu in the Pacific Ocean. After release, rocket boosters accelerate it to about Mach 4.8. When the X-51A separated from the rocket, the SJY 61 engine was initially supplied with a mixture of ethylene and JP-7 jet fuel, and then completely supplied with JP-7 jet fuel. The flight altitude reached approximately 70,000 feet and the maximum speed was Mach 5. According to the data transmitted by its onboard sensors, the test ended after about 200 seconds of engine operation due to technical problems. In the fourth test, the X-51A was released from an altitude of approximately 15,000 meters and accelerated to Mach 5.1 over the next 26 seconds. It flew about 426 kilometers in just six minutes, setting a record for the longest flight distance.

Fig. 4. X-51A aircraft mounted under a B-52 bomber.

3.2 Design Points

High speed aerodynamics, thermal management and materials science are among the most important technical challenges in hypersonic vehicle design. High-speed aerodynamics involves understanding and predicting complex flow characteristics at high speeds, which directly affect vehicle stability and control. Thermal management is critical because the extreme temperatures generated during hypersonic flight can damage or destroy conventional materials. The challenges of materials science include developing materials that can withstand these temperatures while maintaining structural integrity. To address these challenges, researchers employ computational fluid dynamics (CFD) to simulate and predict aerodynamic behavior, enabling more accurate design and optimization. For thermal management, advanced cooling systems and heat-resistant materials, such as ceramic matrix composites, have been developed. These materials not only withstand high temperatures, but also provide the strength and durability necessary for hypersonic flight.

As a promising aerodynamic configuration of hypersonic vehicles, waverider has attracted much attention in recent years. Its unique design makes it have many advantages in hypersonic flight, especially in improving lift-drag ratio and flight efficiency. The design principle of the waverider is to use the shock wave generated by the vehicle's forebody to form a continuous compression surface, thereby providing additional lift to the vehicle. This design not only improves the aerodynamic performance of the aircraft under hypersonic conditions, but also significantly reduces energy consumption during flight.

In the civil field, waverider technology also has broad application prospects. As hypersonic transportation and space exploration demand increases, waverider vehicle design concepts provide new directions for future high-speed vehicle development. Its efficient aerodynamic performance can significantly reduce flight time and energy consumption, which is of great significance for achieving rapid global transportation and reducing the cost of space exploration.

The design and development of Waveriders faced many technical challenges. First, aerodynamic heating in hypersonic flight environments places extreme demands on vehicle materials and thermal protection systems. The team needed to develop materials that could maintain stable performance at extreme temperatures and design effective thermal protection systems to ensure structural safety at high speeds. Secondly, the complex aerodynamic environment puts forward higher requirements for vehicle control and navigation systems. Flow variations and shock disturbances in hypersonic flight pose significant challenges to vehicle stability and controllability, requiring advanced control algorithms and sensor technology to achieve accurate flight control. In addition, sustainability requirements have brought new directions for advancing technology. Traditional hydrocarbon fuel combustion faces efficiency bottleneck and emission problem. In the current literature, rotary detonation engine (RDE) and low temperature clean propellant technology such as liquid hydrogen and liquid methane are becoming hot research topics (such as STRIVE project of EU). These green propulsion technologies, which aim to achieve higher thermal efficiency and lower pollution, are key to future hypersonic vehicles being widely used in civil applications. In terms of green propulsion, research on rotary detonation engine (RDE) has moved from concept demonstration to engineering prototype stage. The detonation wave combustion mode can improve thermal efficiency by about 25% and significantly reduce nitrogen oxide emissions. At the same time, the application of cryogenic propellants such as liquid hydrogen and liquid methane not only has high specific impulse, but also is convenient to combine with regenerative cooling technology to absorb heat by using fuel flowing through the engine wall surface, realizing the integration of propulsion and thermal management. The European Union's STRIVE programme has demonstrated that the use of green liquid hydrogen (produced from solar-electrolyzed water) can reduce life-cycle carbon emissions from hypersonic flight by nearly 90%. These green propulsion technologies are key to unlocking sustainable commercial operations for hypersonic vehicles.

To overcome these challenges, researchers have conducted extensive research and innovation in the fields of materials science, thermal protection technology and flight control. New high temperature materials and composites are being developed to provide improved thermal protection and structural strength for Waverider vehicles. At the same time, advanced cooling technology and thermal management systems are constantly being optimized to effectively reduce vehicle surface temperatures. In terms of flight control, researchers have used artificial intelligence and machine learning techniques to develop smarter control systems that can monitor the flight environment in real time and automatically adjust flight parameters to ensure stable flight under complex conditions.

Despite many challenges, significant progress has been made in the development of Waverider technology. Through continuous experiments and tests, researchers have accumulated abundant flight data, which provide important basis for optimizing the design and improving the performance of waverider aircraft. In the future, with the continuous maturity and application of related technologies, waverider vehicles are expected to play a greater role in military and civilian fields, paving a new path for human high-speed flight and space exploration.

The development of waverider technology depends not only on the progress of single discipline, but also on interdisciplinary cooperation. Experts from multiple fields, including materials scientists, aerodynamic engineers, thermal physicists, and control experts, work closely together to drive continued innovation and development of Waverider technology. This interdisciplinary cooperation mode provides an effective way to solve complex engineering problems and lays a solid foundation for the development of hypersonic vehicles in the future. With the continuous progress of technology, the waverider will show its unique advantages in a wider range of fields, bringing more possibilities for aerospace undertakings.

3.3 Innovation Progress

With the development of waverider technology from theoretical exploration to engineering application, configuration innovation gradually presents the characteristics of multi-dimensional breakthrough: in shock control dimension, conical guidance waverider realizes aerodynamic efficiency jump through shock angle gradient optimization; in theoretical method dimension, three-dimensional kissing theory constructs a new paradigm for asymmetric flow field design; in dynamic adaptability, variable configuration design breaks physical constraints of fixed geometry. These three directions represent the innovative paths of aerodynamic refinement, theoretical universality and functional intelligence respectively. Their commonness lies in that they systematically improve the comprehensive performance of waverider in complex flight environment through in-depth analysis of physical mechanism and integration of multidisciplinary technologies. The following typical cases demonstrate technological breakthroughs and engineering verification results under different innovation paths.

Conical guided waverider vehicle. As a classical configuration of hypersonic vehicle design, the core of cone-guided waverider vehicle is to achieve aerodynamic efficiency jump through precise control of leading edge shock wave. Nasa's x-43b demonstrator uses a double-cone nose fuselage design. The angle of the front cone shock gradually changes from 60 ° to 30 °, forming continuous shock layer interference. By optimizing the shock compression gradient, the forebody drag is reduced effectively, and the inlet pressure is increased by utilizing the recompression effect of the flow in the aft cone. Wind tunnel tests show that the lift-drag ratio of the double-cone forebody configuration is 18% higher than that of the conventional single-cone configuration at Mach number 8. The principle is that the change of shock angle gradient reduces the risk of boundary layer separation, thus maintaining the stability of the flow field. In addition, the axisymmetric characteristics of conical waverider vehicles provide good pressure recovery over a wide range of velocities. Flight test data from the X-43b demonstrated the reliability of shock attachment and flow field control in flight across a range of speeds.

Kiss wave. The three-dimensional kissing theory proposed by Chinese Academy of Sciences breaks through the limitation of traditional axisymmetric flow field and adjusts the shock shape adaptively through local curvature. Based on the mathematical modeling of non-uniform shock flow field, the leading edge of the wave multiplier is designed as the envelope of several kissing cones, and the dynamic matching between shock surface and free flow is realized. At Mach number 8, the waverider configuration using three-dimensional kissing theory exhibits a pressure recovery coefficient of 0.85 due to its active compensation mechanism for lateral pressure gradients in the shock layer. The numerical simulation results show that the inlet velocity nonuniformity can be reduced to less than 5% by optimizing the leading edge curvature distribution, and the combustion efficiency of scramjet can be improved significantly. The CAS team further combined this theory with variable Mach number design to develop a wide velocity domain waverider that can adapt to the Mach 5-10 range. Its volume ratio is 23% higher than that of the traditional cone guidance configuration, providing a new way for the practical application of hypersonic vehicles.

Mutated waverider. DARPA's Manta program creatively combines shape memory alloys (SMA) with aerodynamic shape dynamics to achieve real-time adaptive tuning of aircraft shapes. The configuration uses titanium-nickel smart skin technology to dynamically balance lift-drag ratio and thermal load distribution in transonic flight by triggering continuous deformation of the wing sweep angle from 75 ° to 30 ° through temperature excitation. Wind tunnel test data show that the lift drag ratio can be increased by 12% and the leading edge stagnation temperature can be reduced by more than 300K. The innovation of Manta was to couple active deformation mechanisms with shock control of the waverider body-increasing wing sweep angle to suppress shock detachment as the vehicle accelerated to Mach 6 and decreasing sweep angle to enhance lift coefficient during low-speed climb. The dynamic adjustment strategy breaks through the limitation of velocity domain of traditional fixed configuration waverider and provides a technical paradigm for multi-mission adaptability of hypersonic vehicle. In flight testing, Manta demonstrated 30 consecutive configuration switches in the Mach 5-7 range, demonstrating the reliability of smart materials in extreme thermal environments.

It is based on the accumulation of early technical verification that the current research focus has shifted to intelligent empowerment. For example, in the field of navigation control, AI multi-source fusion algorithms are working to solve autonomous flight problems in extreme conditions such as black barriers; in terms of thermal management, research is moving from X-33 passive protection to 'perception-response' systems integrating smart materials and active cooling; in propulsion systems, green technologies such as rotary detonation engines (RDE) are focusing on future sustainability requirements.

4 Conclusions

To sum up, hypersonic technology has undergone a clear evolution from theoretical conception to engineering verification, and then to system intelligence. Early basic aerodynamic theory (e.g. lifting body, waverider) pointed out the direction for development; mid-term series flight demonstration projects (e.g. X-33, HIFiRE) overcome key technical bottlenecks; and the current research frontier focuses on the intelligent and practical realization of hypersonic vehicles through AI, smart materials and green propulsion technologies. This evolution provides a clear roadmap for future technological development.

Hypersonic vehicles will play an irreplaceable role in both the present and the future. In the military field, future hypersonic vehicles will develop in the direction of further improving cruise speed, range and strike accuracy, and countries will further invest a lot of funds to support related research projects. In the field of transportation, further increase in cruise speed to improve transport efficiency is also a development direction. In addition, in the pursuit of higher speed and higher efficiency, flight safety and comfort are also key issues that need to be addressed by hypersonic vehicles in this field. Looking ahead, future research directions include the optimization of aerodynamic designs for better fuel efficiency and reduced drag, the development of advanced thermal management systems to protect against heat damage, and the exploration of sustainable propulsion methods. Furthermore, the integration of hypersonic vehicles into broader aerospace systems, such as space launch vehicles and global rapid transport networks, presents new challenges and opportunities for innovation.

References

1. Gao M, Wang J, Liu J, et al. Analysis and insight of the first operational use of Russian Dagger hypersonic missile[J]. Tactical Missile Technology,2022,No.216(06):116-120.DOI:10.1016/j.cja.2023.12.01
2. Hou N, Liu X.Y, Analysis of the U.S. FY 2021 defense high-tech budget proposal[J]. Defense Science and Technology,2020,41(04):42-51.DOI:10.1002/mhw.331
3. Wang L.P, Zhao S, Jiang C.J, et al. Development of foreign hypersonic weapons[J]. Aerospace electronic countermeasures,2020,36(05):6164.DOI:SUN:FHDD.0.2013-02-006
4. Wang Q.L, Chen W.F, Development of lift body structure vehicle and its application prospect[C]. Proceedings of the National Symposium on Hypersonic Aerodynamics (Thermal 13th). 2023:124-126.
5. An S , Wang G , Liu J ,et al.Antinoise Aerodynamic Parameter Estimation Approach for Hypersonic Vehicle Using Dynamic Equation and Flight Data[J].Journal of Aerospace Engineering, 2025(3):38.DOI:10.1061/JAEEEZ.ASENG-6056.

6. Wang L , Xue L , Liu Y ,et al.Working medium selection for Hypersonic Vehicle Closed Brayton Cycle Energy Systems[J].Applied Thermal Engineering, 2025, 274(PartB).DOI:10.1016/j.applthermaleng.2025.126704.
7. Han J , Cao Y , Yeo T S ,et al.Simultaneous Scene Imaging and GMTI Scheme With Multiple Beamforming for Hypersonic Vehicle-Borne Dive-Trajectory MC-SAR[J].Geoscience and Remote Sensing, IEEE Transactions on, 2024, 62(000):1-17.DOI:10.1109/TGRS.2024.3351311.
8. Kai A N , Zhenguo W , Wei H .Adaptive learning-based optimal tracking control system design and analysis of a disturbed nonlinear hypersonic vehicle model[J].Science China(Technological Sciences), 2024(6).DOI:10.1007/s11431-023-2616-3.
9. Xu W , Liao Y , Wang X ,et al.Range-Varying Sliding Mode-Based Integrated Guidance and Control for Hypersonic Vehicle With Multi-Constraints[J].International Journal of Robust & Nonlinear Control, 2025, 35(6).DOI:10.1002/rnc.7804.
10. Zhao X , Quan S , Han B ,et al.Optimization of Midcourse Guidance Trajectory for Hypersonic Vehicle Swarms Using the Radau Pseudospectral Method[C]//International Conference on Autonomous Unmanned Systems.Springer, Singapore, 2025.DOI:10.1007/978-981-96-3568-9_21.
11. Ma T L, Xue P, Jiang L L, et al. An efficient and high-precision aerodynamic modeling method for hypersonic vehicle optimization design[J]. Aerospace Science and Technology, 2025, 164: 110382. DOI:10.1016/j.ast.2025.110382