Reports of China's Basic Research

Shanyi Du *Editor*

Key Basic Scientific Problems on Near-Space Vehicles

ZHEJIANG UNIVERSITY PRESS
浙江大学出版社

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Reports of China's Basic Research

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Editor

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ISSN 2731-8907 ISSN 2731-8915 (electronic)
Reports of China's Basic Research
ISBN 978-981-19-8906-3 ISBN 978-981-19-8907-0 (eBook)
https://doi.org/10.1007/978-981-19-8907-0

Jointly published with Zhejiang University Press
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Zhejiang University Press.

Translation from the Chinese Simplified language edition: "近空间飞行器的关键基础科学问题" by Shanyi Du, © 浙江大学出版社 2020. Published by 浙江大学出版社. All Rights Reserved.

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The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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Preface to the Series

As Lao Tzu said, "A huge tree grows from a tiny seedling; a nine-storied tower rises from a heap of earth." Basic research is the fundamental approach to fostering innovation-driven development, and its level becomes an important yardstick for measuring the overall scientific and national strength of a country. Since the beginning of the 21st century, China's overall strength in basic research has been consistently increasing. With respect to input and output, China's input in basic research increased by 14.8 times from 5.22 billion yuan in 2001 to 82.29 billion yuan in 2016, with an average annual increase of 20.2%. In the same period, the number of China's scientific papers included in the Science Citation Index (SCI) increased from lower than 40,000 to 324,000; China rose from the 6th to the 2nd place in global ranking in terms of the number of published papers. In regard to the quality of output, in 2016, China ranked No. 2 in the world in terms of citations in nine disciplines, among which the materials science ranked No. 1; as of October 2017, China ranked No. 3 in the world in the numbers of both Highly Cited Papers (top 1%) and Hot Papers (top 0.1%), with the latter accounting for 25.1% of the global total. In talent cultivation, in 2006, China had 175 scientists (136 of whom from the Chinese mainland) included in Thomson Reuters' list of Highly Cited Researchers, ranking 4th globally and 1st in Asia.

Meanwhile, we should also be keenly aware that China's basic research is still facing great challenges. First, funding for basic research in China is still far less than that in developed countries—only about 5% of the R&D funds in China are used for basic research, a much lower percentage than 15%–20% in developed countries. Second, competence for original innovation in China is insufficient. Major original scientific achievements that have global impact are still rare. Most of the scientific research projects are just a follow-up or imitation of existing research, rather than groundbreaking research. Third, the development of disciplines is not balanced, and China's research level in some disciplines is noticeably lower than the international level—China's Field-Weighted Citation Impact (FWCI) in disciplines just reached 0.94 in 2016, lower than the world average of 1.0.

The Chinese government attaches great importance to basic research. In the 13th Five-Year Plan (2016–2020), China has established scientific and technological innovation as a priority in all-round innovation and has made strategic arrangements to strengthen basic research. General Secretary Xi Jinping put forward a grand blueprint of making China into a world-leading power in science and technology in his speech delivered at the National Conference on Scientific and Technological Innovation in 2016 and emphasized that "we should aim for the frontiers of science and technology, strengthen basic research, and make major breakthroughs in pioneering basic research and groundbreaking and original innovations" at the 19th CPC National Congress on October 18, 2017. With more than 30 years of unremitting exploration, the National Natural Science Foundation of China (NSFC), one of the main channels for supporting basic research in China, has gradually shaped a funding pattern covering research, talent, tools, and convergence and has taken action to vigorously promote basic frontier research and the growth of scientific research talent, reinforce the building of innovative research teams, deepen regional cooperation and exchanges, and push forward multidisciplinary convergence. As of 2016, nearly 70% of China's published scientific papers were funded by the NSFC, accounting for 1/9 of the total number of published papers all over the world. Facing the new strategic target of building China into a strong country in science and technology, the NSFC will conscientiously reinforce forward-looking planning and enhance the efficiency of evaluation, so as to achieve the strategic goal of making China progressively share the same level with major innovative countries in research total volume, contribution, and groundbreaking researchers by 2050.

The series of *Advances in China's Basic Research* and the series of *Reports of China's Basic Research* proposed and planned by the NSFC emerge against such a background. Featuring science, basics, and advances, the two series are aimed at sharing innovative achievements, diffusing performances of basic research, and leading breakthroughs in key fields. They closely follow the frontiers of basic research developments in China and publish excellent innovation achievements funded by the NSFC. The series of *Advances in China's Basic Research* mainly presents the important original achievements of the programs funded by the NSFC and demonstrates the breakthroughs and forward guidance in key research fields; the series of *Reports of China's Basic Research* shows the core contents of the final reports of Major Programs and Major Research Plans funded by the NSFC to make a systematic summarization and give a strategic outlook on the achievements in the funding priorities of the NSFC. We hope not only to comprehensively and systematically introduce backgrounds, scientific significance, discipline layouts, frontier breakthroughs of the programs, and a strategic outlook for the subsequent research, but also to summarize innovative ideas, enhance multidisciplinary convergence, foster the continuous development of research in concerned fields, and promote original discoveries.

As Hsun Tzu remarked, “When earth piles up into a mountain, wind and rain will originate thereof. When waters accumulate into a deep pool, dragons will come to live in it.” The series of *Advances in China’s Basic Research* and *Reports of China’s Basic Research* are expected to become the “historical records” of China’s basic research. They will provide researchers with abundant scientific research material and vitality of innovation and will certainly play an active role in making China’s basic research prosper and building China’s strength in science and technology.

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Preface

The major research plan of "Key Basic Scientific Problems on Near-Space Vehicles" (hereinafter referred to as the Plan) is the first systematic basic hypersonic research program in China. From its inception in 2007 to its successful completion in 2016, the Plan lasted nine years, funded a total of 173 projects, and the funding totaled 190 million yuan. From the perspective of major national needs and scientific discipline development, the Plan focuses on four key scientific issues: aerodynamics in a near-space flight environment; advanced propulsion theories and methods; ultralight materials/structures, thermal environment prediction, and thermal protection; and intelligent autonomous control theories and methods for hypersonic vehicles. The Plan has conducted systematic basic research by implementing top-level design, proactive guidance, strategic layout, dynamic adjustment, integrated innovation, and promotion of interdisciplinary efforts.

The Plan has achieved systematic and innovative research results in terms of interdisciplinary theories and methods and innovative techniques. The evaluation expert group believes that implementing the Plan has provided China with the following progress: a distinctively Chinese basic research framework for near-space hypersonic vehicles; comprehensively improved research capability with respect to key scientific issues; gap bridging within several theories and technological methods; and strong support for breakthroughs of key technologies for major national projects. The Plan has reached the highest research level in the world and realized a leapfrog development. Simultaneously, the Plan has integrated and cultivated numerous outstanding talent and innovation teams for hypersonic vehicle research in China; notably, some of them have already grown to be the backbone of the basic research and key technologies of hypersonic vehicles in the country.

Since the completion of the Plan in 2016, the strategic, revolutionary, and disruptive natures of near-space hypersonic vehicle technologies have gained greater consensus and received unprecedented attention from all major powers in the world. The unprecedented research progress of near-space hypersonic vehicle technologies has shifted from key technology to weapons and equipment development, manifesting the trend of accelerated transformation and deployment. The multiple key breakthrough technologies that China has realized, along with a series of successful flight tests, have attracted global attention, which not only evidence an accelerated development trend but also transform the nation from a follower to a leader in the field of near-space hypersonic vehicle technologies. This has resulted from the continuous improvement of our comprehensive national strength, the unremitting efforts of our scientific researchers, and the systematic layout of basic research, demonstrating the strategic, forward-looking, and critical contribution of the Plan. According to *Aviation Week*, a U.S. journal, the Plan has been a well-coordinated and highly effective hypersonic research program leveraging efforts and resources from the entire country. The Plan not only has an astonishing depth and breadth in terms of research but also has achieved a remarkable number of major achievements in a relatively short duration.

In the following three years after the conclusion of the Plan, on the basis of the Advanced Hypersonic Weapon (AHW) program, the U.S. Navy, Air Force, and Army have focused on developing submarine-launched/land-launched/air-launched hypersonic boost-glide missile weapons. This includes the Hypersonic Conventional Strike Weapon (HCSW), the Air-Launched Rapid Response Weapon (ARRW), the Common-Hypersonic Glide Body (C-HGB), and the Long-Range Hypersonic Weapon (LRHW). The U.S. Defense Advanced Research Projects Agency (DARPA) continues to promote the verification of hypersonic cruise missiles under the Hypersonic Air-Breathing Weapon Concept (HAWC) program, and the ground-based verification of turbine-based combined cycle engines has also made significant progress. In addition, Lockheed Martin and Boeing have unveiled their hypersonic aircraft concept and development plans. To strengthen basic research and the transformation of scientific and technological achievements, the USA continued to implement the Hypersonic International Flight Research and Experimentation (HIFiRE) program and launched the Hypersonic Routine and Affordable eXperimentation (HyRAX) program. GOLauncher 1 (GO1) received the U.S. Air Force designation X-60A for hypersonic flight research and has been used for low-cost and large-scale flight tests for a range of hypersonic technologies, including scramjet engines, high-temperature materials, and autonomous control. Russia has also rapidly progressed in hypersonic weapons. The air-launched Kinzhal (Dagger) hypersonic missile and the Avangard hypersonic glide vehicle are probably already in service and on combat duty. Russia has become the very first country in the world to be officially equipped with hypersonic weapons and is still making every effort to accelerate the development of the Zircon hypersonic missile. Other countries and regions, such as Europe and Japan, continue to explore hypersonic aircraft technology and concepts; the UK initiated an aircraft development program after a breakthrough in key technologies of the Synergetic Air-Breathing Rocket Engine (SABRE). These programs could set off a new wave of transformation in the field of hypersonic flight platforms.

In the three years after the Plan, with the rise of China's hypersonic technologies, the global hypersonic industry has focused its attention on China. In addition to a series of successful flight tests of China's hypersonic vehicle technologies reported by foreign media, the official debut of Dongfeng-17 in the military parade celebrating the

70th anniversary of the founding of the People's Republic of China caused a worldwide sensation; the public debut of the near-space hypersonic universal flight test platform "Lingyun" funded by the Plan has also been a major support to the development of key hypersonic technologies such as the scramjet engine. The detonation-driven hypersonic shock tunnel with the highest performance to date has attracted wide research attention from international peers. The boundary layer transition flight test of hypersonic vehicles was a complete success. Additionally, the hypersonic flight test of Xingkong-2 (Starry Sky-2) verified the next-generation advanced technologies, such as waverider aerodynamic designs, dredging thermal protection, and static instability control. The successful flight tests of Tianxing-1 and Chongqing Liangjiang Star developed by commercial space companies have provided a broader platform to improve the knowledge of hypersonic flight and facilitate technology transfer. The flight wind tunnel laboratories may become a series of laboratories. China's reusable launcher program and the Tengyun spaceplane project have been unveiled, and the air-breathing combined cycle engine technology has been verified by testing. The fundamental and innovative research results of new hypersonic aerodynamic layout I-plane and high temperature-resistant ceramic matrix composite (CMC) materials have been published in prestigious journals both at home and abroad. The above developments not only clearly reflect the achievements and influence of China in the field of hypersonic technology but also show its improvement in basic research capability, self-confidence, and innovation capability.

Hypersonic technology is a strategic commanding point in the future aerospace field that can guarantee national security, contribute to economic development, and transform people's quality of life. Moreover, hypersonic technology drives scientific and technological developments and reflects scientific and technological capabilities. The implementation and subsequent development of the Plan have verified our understanding of the development trend of hypersonic technology. Simultaneously, we are deeply aware that what has just been unveiled was merely a prologue of hypersonic technology and that we are still a long way from achieving widespread and mature applications. Basic research remains the cornerstone for improving our understanding of hypersonic flight and technological breakthroughs as well as the strategic engine to produce original results, thus rendering us a leader in the field. Focusing on the forward-looking layout is an important asset to seize the high ground in science and technology; giving full play to the role of basic research in the whole chain of innovation is the key to fulfilling the major needs of the country. Furthermore, a high-level and stable-scale research team is crucial for realizing leapfrog development. The report to the 19th National Congress of the Communist Party of China highlighted that "we should aim for the frontiers of science and technology, strengthen basic research, and make major breakthroughs in pioneering basic research and groundbreaking and original innovations." Although the Plan has concluded, basic research on hypersonic technology must be intensified as new demands will emerge at a new starting point to help China increase aerospace strength and contribute more to national rejuvenation.

This book could not have been completed without the hard work of Tianjin University, China Academy of Aerospace Aerodynamics, University of Chinese Academy of Sciences, Beihang University, the Institute of Mechanics of Chinese Academy of Sciences, Sichuan University, China Aerodynamics Research and Development Center, National University of Defense Technology, Nanjing University of Aeronautics and Astronautics, Northwestern Polytechnical University, Peking University, Harbin Institute of Technology, Tsinghua University, Dalian University of Technology, Wuhan University of Science and Technology, the Aerospace Research Institute of Materials and Processing Technology, and all the participants of the Plan. We would like to express our sincere gratitude to all the institutes and individuals involved.

Harbin, China Shanyi Du

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Project Overview

Shanyi Du, Daining Fang, Haiyan Hu, Zhang Ren, Zhenguo Wang, Jing Fan, and Youda Ye

1 Introduction

Near space is generally defined as the airspace in the altitude band between approximately 20 and 100 km, where the atmospheric density drastically varies. For a long period of time, this airspace with special atmospheric characteristics was neglected in the development of space vehicles, or scientists were forced to abandon their in-depth explorations owing to the extreme difficulty of its special scientific problems. Modern technological development shows that if the thin air in this airspace could be fully utilized to provide an aerodynamic lift for the aircraft and used as the oxidizer for suction engines, it would reduce the aerodynamic drag and heating, realizing efficient and reliable intra-atmospheric flight at hypersonic speeds. It is this thin layer of air that presents many difficulties and poses a formidable challenge to human cognitive ability and technical implementation.

Near-space vehicles are vehicles that can fully utilize the characteristics of the near-space environment and fly stably in near space. They are the most effective tools to perform missions such as rapid long-range transport, precision strike, long-range real-time reconnaissance, persistent high-altitude surveillance, intelligence gathering, and communication relay. The special strategic value of near-space vehicles has received wide research attention globally. Therefore, the development of near-space vehicles is significant to national security and the peaceful uses of outer space; it is one of the focal points of the current international competition for space technology, as well as a reflection of comprehensive national power. Near-space hypersonic flight has become the strategic high ground of international competition in aerospace technology in the twenty-first century, and many developed countries have listed it as an important national strategic goal.

Boost-glide maneuvering and hypersonic cruise are critical technologies being developed by the U.S., Russia, and other countries in the last decade. The goal is to achieve high Mach number (*Ma*) flight in near space for a long period of time using powered-phase depressed trajectories, high lift-to-drag ratio configuration, and special anti-insulation design. In the field of boost-glide maneuvering, the HTV-2

S. Du (ed.), *Key Basic Scientific Problems on Near-Space Vehicles*, Reports of China's Basic Research, https://doi.org/10.1007/978-981-19-8907-0_1

project jointly supported by the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force as well as the Advanced Hypersonic Weapon (AHW) supported by the U.S. Army are representative projects that have researched hypersonic boost-glide vehicles. HTV-2 completed two flight tests in 2010 and 2011, both of which failed. In the field of hypersonic cruise, in the mid-1990s, the National Aeronautics and Space Administration (NASA) proposed the Hyper-X, which aimed to investigate and validate scramjet engine technology for hypersonic aircraft and reusable space transportation systems. X-51A in the Hyper-X program completed two successful flights, but it remains a power system verification program. Furthermore, the U.S. Air Force and Navy have deployed the HyTech and HyFly programs. Russia is using the Topol-M missile as an effective countermeasure against U.S. missile defense systems; simultaneously, a hypersonic test vehicle Igla is being developed, which will be powered by a hydrogen-fueled engine and fly at *Ma* 6–14. It is mainly used to study major technical issues such as airframe/propulsion integration and flight dynamics of hypersonic test vehicles.

The strategic demand for developing near-space hypersonic technologies originates from the demand for safeguarding national interests, national security, sustainable development of the national economy and scientific exploration, and technological promotion. China is a late comer in the field of near-space vehicles, particularly in related basic research; thus, our technological accumulation is relatively weak. In 2006, the State Council of China released the "Outline of the National Medium- and Long-Term Science and Technology Development Program (2006–2020)" from the perspective of national strategic layout, clearly proposing that defense science and technology will provide support for safeguarding national security. In the section "Major mechanical issues in aeronautics and space science," which is one of the 18 basic scientific issues, it was proposed that priorities shall be placed on studying the mechanical issues involving supersonic propulsion systems and super high-speed collision; multidimensional propulsion systems and theory of complex movement control; theory of compressible turbulent flows; high-temperature thermodynamics; magnetic fluid and plasma dynamics; microfluid and microsystem dynamics; and structural dynamics of new materials. Simultaneously, a number of major national projects or science and technology projects closely related to near-space vehicle technologies were launched.

In 2001, eight academicians from the Division of Mathematics and Physics and the Division of Technological Sciences of the Chinese Academy of Sciences (CAS) conducted in-depth research on the role, status, and development of aerospace vehicles. In their proposal entitled "Severe Situation of Aerospace Security and Current Countermeasures of China in the 21st Century," they highlighted that the lack of attention to basic research has severely restricted China's ability to innovate independently and acquire the technology reserve needed to ensure aerospace security in the future. Consequently, the Department of Mathematical and Physical Sciences of the National Natural Science Foundation of China (NSFC) pioneered the launch of a major research plan of "Some Major Basic Problems on Aerospace Vehicles" in 2002. This was the first time that China launched a basic research plan for space vehicles at the national level, aiming at guiding and gathering all parties to study the key problems of space vehicles that fulfill national strategic needs and have original innovative ideas to lay the foundation of technological innovation for guiding the development of China's future space vehicles.

With the implementation of the above-mentioned plan, near-space hypersonic vehicle technologies have played an increasingly important core and strategic role in the development of future aerospace vehicles, and relevant major national needs will be strengthened. In 2006, the Department of Mathematical and Physical Sciences of the NSFC organized a seminar on the development of near-space vehicles and major basic scientific issues, which received positive response and considerable attention from aerospace departments, CAS, universities, and other relevant departments and experts. In that seminar, the requirement background, development status, and key basic science issues and technologies of near-space vehicles were discussed critically and in depth. The NSFC has clearly defined the guiding principle that "basic research should serve the major demand of the country." Through the funding of major research plans that reflect the "combination of serving national goals and encouraging free exploration," the major research plan of "Key Basic Scientific Problems on Near-Space Vehicles" (hereinafter referred to as the Plan) was launched in 2007 and successfully concluded at the end of 2015.

1.1 Overall Layout

Near-space hypersonic technologies will revolutionize national security and daily life in the future. It will become a strategic commanding point in the international competition of aerospace technology in the twenty-first century, and many countries have defined it as a national strategic goal. The Plan, as an extension and sublimation of the major research plan "Some Major Basic Problems on Aerospace Vehicles," primarily focuses on the key basic problems of near-space vehicles and addresses the fundamental, strategic, and forward-looking scientific problems in the research on near-space vehicles.

Comparatively speaking, the Plan has a more focused research direction, more targeted key scientific issues, and more in-depth and challenging research contents, which reflects the process of scientific research evolving from a general, superficial, and quantitative understanding to a specialized, deep, and qualitative understanding.

The Plan has the following goals, namely, the overall objectives: (i) to develop innovative theories and methods for key basic scientific problems of near-space vehicles and to provide a fundamental source for the formation and development of related technologies; (ii) to make a breakthrough in the innovation of technology methods, to enhance China's independent innovation capability in related fields, and to support the leapfrog development of related technologies; (iii) to build and cultivate a team of outstanding talent at the global forefront in this field and have theoretical as well as source technological innovation capabilities and to support the development of China's near-space vehicles.

Following the general idea of "definite objective, stable support, integration and promotion, and leap-forward development," the Plan is designed to conduct innovative basic research on the key scientific issues of near-space vehicles, strengthening the top-level design and refining scientific goals, so as to facilitate interdisciplinary research and foster innovative talent. To achieve leapfrog development in several key areas and important directions, several innovative concepts, theories, and methods in the field of near-space vehicles will be developed, which will enhance China's independent innovation capability in the aerospace field and support the development of related technologies. After many discussions, the Steering Committee of the Plan decided to categorize the scientific problems into two levels: basic research driven by background needs and forward-looking exploratory basic research. During the implementation of the Plan, two main lines of research were highlighted: basic research that promoted the development of related disciplines and basic research that led and supported the application of near-space vehicle research and key technologies. The two main lines were organically intertwined to develop a next-generation source innovation capability and forward-looking science and technology reserve for China's near-space vehicle development.

To solve the key scientific issues in the Plan, milestones were established in the implementation process, and work in different phases was prioritized.

Phase 1 was the seeding phase, which focused on developing new theories, methods, and concepts, exploring and discovering unknown scientific problems, promoting related research works, and developing a comprehensive plan for key scientific issues.

Phase 2 was the growth and integration phase, which focused on strategic and forward-looking basic research, the supporting role of basic research in applied research, and the transformation and radiation of results. This phase also strengthened key directions, actively promoted integration and intersection, and eventually achieved breakthroughs in key directions.

Phase 3 was the sublimation phase, which focused on further promoting deep integration and intersection, striving to improve the level of results, and promoting sublimation of results. This phase also strengthened team and platform construction and achieved leapfrog development.

From the perspective of the overall implementation process of the Plan, the three phases complemented each other, and each phase had its own defined focus as well as objectives. By giving examples with successful experiences, the Plan was conducted smoothly.

To ensure that the objectives of each phase were accomplished with high quality, the following measures were adopted during the implementation of the Plan.

(i) Full play was given to the Steering Committee's role in the top-level design. Starting from the project guidelines of the Plan, attention was given to refining the guidelines for each phase and preparing the guidelines according to the tasks and objectives of each phase. At the annual meeting of the Steering Committee, the research directions that required strengthening in the next phase were clarified based on the progress of the Plan, and the layout for each research area was adjusted to balance the developments in all directions.

(ii) Project review was strengthened, and project quality was ensured. The applied projects were reviewed to check whether they complied with the scope and requirements of the guidelines. Projects that failed to comply with the guidelines would not be funded even if they were highly innovative or with positive reviews.

(iii) Progress checks were strengthened. All projects were reported at the annual academic exchange meetings, and the Steering Committee conducted a dynamic analysis of the operational status of the Plan to identify problems and provide timely solutions. Support was strengthened for research directions with a weak domestic research base; timely correction was provided for projects that deviated from the key scientific issues in the Plan; and follow-up funding was provided for projects in smooth progress. Simultaneously, we strengthened the top-level design and combined the research teams in similar academic directions to form clusters of projects with identical objectives.

(iv) Academic exchanges were emphasized. Interdisciplinary research and collaboration were promoted through annual academic exchange meetings and small high-end symposiums, where the results were showcased. Engineering experts in the field of near-space vehicles were regularly invited to meetings to report their work and exchange ideas, which enables the project directors and academic backbones in the Plan to develop a comprehensive understanding of the latest trends and application needs of relevant domestic and international studies, promotes engineering applications of the research results, and provides a broad platform for communication and collaboration among the developers in the Plan.

(v) Talent cultivation was always a top priority. Through the Plan, a wealth of young high-level academic backbone talent was cultivated to form an outstanding academic team in the field of near-space vehicles. Consequently, China's academic research in related fields has reached an international advanced level, laying a foundation for the sustainable development of scientific research in the field of near-space vehicles.

1.2 Guidelines and Approaches

The guidelines of the Plan are as follows: to take demands as the traction and basics as the base; to make approaches novel and explorations fundamental; to reserve for the future, leap forward and improve. That is, the Plan is based on basic research, distinct from but connected to the National Science and Technology Major Project, the National High-Tech R&D Program (863 Program), and the National Basic Research Program (973 Program). The scientific problems involved highlight three key points—long term, high speed, and commonality—which are fundamental and forward-looking.

The overall implementation approaches of the Plan are as follows. In the first year, we focused on the deployment of fostering projects and analyzed the shortcomings and weaknesses according to the applications and funding. In the second year, we optimized the project deployment, developed the key projects, adjusted the funding direction and intensity in time, and made reasonable suggestions for the projects that deviated from the objectives. In the third year, we strengthened the key projects, carefully identified the major engineering requirements, and developed clear guidelines and application requirements. In the fourth year, we began to deploy integrated projects, adjusted the guidelines for key projects according to the deployment, and explored the mode of organizing integrated projects from advantageous research directions. In the fifth year, we focused on the deployment of those integrated projects that reflected the top-level design thinking, renewed funding for projects with outstanding progress, fully understood the progress of participating projects, summarized the achievements carefully, identified the problems in a timely manner, and conducted the mid-term evaluation objectively. In the sixth year, the focus was on the in-depth integration and sublimation of projects, pushing "small synergy" toward "large synergy," and producing more highlights and research characteristics. The seventh year to the ninth year marked the closing stage, focusing on the refinement and sublimation of results: all important progress and achievements since the implementation of the Plan were summarized and condensed.

The Plan always adhered to the concept of leap-forward development in the process of implementation, aiming at further consolidating the foundation of basic research support for the high-tech development of China's near-space vehicles. We insisted on "doing what must be done and not doing what must not be done," focused on the selected key basic research areas related to the future development of near-space vehicles, defined limited objectives, made breakthroughs, and used limited resources, the most needed, as a result of which China's basic research on key basic scientific problems of near-space vehicles now have earned a place in the international area and have been exerting a far-reaching influence.

In the Plan, the four key scientific issues were considered key funding areas and directions for project deployment. The Steering Committee analyzed and decomposed the difficulties and points of the key scientific issues and selected the problems that will affect the long-term development of near-space vehicles and must be solved first, as well as the basic problems that need to be solved immediately to fulfill major national needs. A relatively reasonable layout was developed to reflect the top-level design of the Steering Committee.

Enhancing key projects was an important feature of the Plan. The Steering Committee adhered to the principles of "major problem, interdisciplinary efforts, resource compilation, and comprehensive integration" and set up different key funding directions according to the importance, maturity, and inheritability of scientific problems. It was explicitly required that applications should reflect the interdisciplinary efforts and advantage complementation between research teams within and among the key scientific issues. For example, two key projects were funded in the areas of "supersonic combustion propagation and stabilization" to improve supersonic combustion efficiency and "active engine cooling" where the research foundation in China is weak. In the areas of "lightweight/multifunctional material and structure integrated design and optimization" and "exploration of new thermal protection material systems," several key projects were funded. With respect to the issue of "hypersonic flight control," a series of key projects on fine attitude, autonomous coordinated, adaptive control, and intelligent control were funded.

Simultaneously, the Steering Committee and the Management Group focused on key projects to drive the development of related fostering projects. After the mid-term evaluation, the Steering Committee strengthened the top-level design and integrated the research into project clusters based on the results of the previous fostering projects and key projects. For example, integrated projects were funded in three interdisciplinary directions: the study of aerodynamic/propulsive/structural couplings of near-space vehicles; the study of multiparameter experimental integration methods and technologies for high-temperature thermal protection materials and structures in ultra-high-temperature (UHT) oxidation environments; and control-oriented modeling and verification of near-space hypersonic vehicle dynamics. These directions improved the synergistic innovation capability of the interdisciplinary directions through integrated projects. Alternatively, it provided a platform for basic research and an interdisciplinary research environment for scientists in different fields, enabling them to achieve continuous refinement and sublimation of research results, promote source innovations, and achieve the purpose of integration.

1.3 Comprehensive Integration and Interdisciplinary Efforts

Scientific researchers are shifting from high differentiation to interdisciplinary efforts. A near-space vehicle is a complex system comprising several subsystems, and different disciplines and subsystems are strongly coupled. Interdisciplinary efforts and integration are therefore its outstanding features. Without a research approach that focuses on multidisciplinary integration, achieving theoretical and methodological breakthroughs, not to mention developing innovative technological approaches, is difficult. The Plan was led by the Department of Mathematical and Physical Sciences, in collaboration with the Department of Engineering and Material Sciences and the Department of Information Sciences, aiming to promote interdisciplinary efforts and integration of mechanics, physics, chemistry, mathematics, material science, information science, and other related basic disciplines.

Specific interdisciplinary efforts were achieved at different levels. First, at the level of key scientific issues, important research results were produced through interdisciplinary efforts. Second, the multidisciplinary integration of key scientific issues was emphasized, which played an important role in helping solve major scientific problems in subsystems. Third, the establishment and implementation of the integrated projects attached importance to the multidisciplinary integration of results from major disciplines to achieve the purpose of integration and sublimation and lay a solid foundation for solving key scientific issues.

(1) Interdisciplinary efforts for research directions of key scientific issues

The four key scientific issues identified in the Plan are problems in four major disciplines: aerodynamics, propulsion, materials and structures, and control. However, the results of each of these research directions highlighted the role of multidisciplinary integration. With the guidance and support of the Plan, a significant number of the fostering projects and key projects reflected this research approach of interdisciplinary integration in their implementation and completion processes. For example, projects including "Fundamental Research on Effect of Nonuniform Edge Blunting on Aerodynamic/Thermal Properties of Waveriders," "New Concept Research on Integration of Thermal and Drag Reduction for Near-Space Hypersonic Vehicles," and "New Method Research for Drag Reduction for Hypersonic Vehicles" provided innovative ideas to solve the contradiction between excellent aerodynamic performance and sharp edges of waveriders and to realize the integration of drag/heat reduction through interdisciplinary research on aerodynamics, aerothermodynamics, physics, thermal protection, and high-temperature materials. The project "Research on a New Concept Compression System for Hypersonic Airflow" proposed a new type of efficient bending surge compression system through interdisciplinarity of propulsion and aerodynamics. The project "Research on Mechanism of Porous Transpiration Cooling in Cavity Flame Stabilizer of Scramjet Engine" involved interdisciplinary research on aerodynamics, combustion, materials, engineering thermal physics, and other disciplines, and improved our understanding of the flow, combustion, heat transfer and mechanism of the cavity flame stabilizer with porous transpiration cooling, thus providing theoretical guidelines for the thermal protection design of scramjet engines. The projects "Theoretical and Experimental Research on Reactionless Microwave Propulsion with Built-in Energy" and "Research on Magnetic Fluid Scramjet Engine Technology" provided an effective technical approach to exploring new propulsion methods through the interdisciplinarity of propulsion, microwave and plasma physics. The project "Research on Toughening Mechanism of ZrB_2-SiC Ultra-High-Temperature Ceramics Against Thermal Shock" was based on interdisciplinary studies of mechanics, material science, physics, and bionics, and revealed the mechanism of the sudden drop in residual strength of ultra-high-temperature ceramics (UHTCs) owing to thermal shock. It effectively overcame the thermal shock failure of ceramics by modifying and optimizing the microstructure of thermal protection materials with reference to the structural laws of biocomposites, thus providing an effective approach to improving the toughness and resistance to the thermal environment as an alternative to searching for new materials. The project "Research on Mechanism of Coordinated Deformation Control of Composite Fuel Tanks with Ultrathin Metallic Liners" combined the interdisciplinary knowledge and methods of mechanics, material science, nanotechnology, and bionics, and used the principle of "bionic gecko foot" to graft carbon nanotubes uniformly onto the surface of the ultrathin aluminum alloy liner, which increased the strength of the interface layer by 28% and ensured deformation coordination between the metallic liner and the composite structure. The research projects related to high-temperature and long-time thermal protection, load-bearing, and wave-transmitting integration radome/window materials further embodied interdisciplinary research efforts on the organic combination of electromagnetism, thermal protection, mechanics, and material science. Projects such as "Multi-Mode Switching Control of Lifting-Body Hypersonic Vehicles/Engines," "Nonlinear Multi-Coupled Flight Dynamics and Control of Hypersonic Waverider Vehicles," and "Strong Robust and Stable Intelligent Autonomous Control of Integrated Structural/Aerodynamic/Flight Control System of Near-Space Vehicles" all involved the interdisciplinary studies of aerodynamics, propulsion and control sciences. The projects "Nonlinear Coupled Dynamics and Thermoelastic Flutter Control of Hypersonic Vehicles" and "Aerodynamic/Thermoelastic Study of Hypersonic Vehicles" explored the mechanism of the heat transfer effect of aerodynamic heating in fluid–structure coupling systems based on a strategy combining computational fluid dynamics (CFD), heat transfer, and computational structural dynamics.

(2) Interdisciplinarity of key scientific issues

The main research directions and funded projects of the key scientific issues reflect the layout of interdisciplinary studies and the further sublimation from "small synergy" to "large synergy." For example, the project "Influence of Nonlinear Aerodynamics with Time Lag on Dynamic Characteristics of Hypersonic Vehicles and Flow Control Thereof" explored the dynamics generated by the unstable motion of hypersonic vehicles from the theoretical and experimental studies of aerodynamics and through interdisciplinarity of control disciplines such as dynamics modeling, system identification, and flight stability analysis. The project "Research on Catastrophe Control in Scramjet Engine" proposed a catastrophe control approach that combines switching control and catastrophe mode transition control through interdisciplinarity of engine and control disciplines. The project "Research on Morphing Structure, Thermal Protection and Active Control of Near-Space Hypersonic Vehicles" combined the knowledge and methods of mechanics, control, and mechanical design, revealed the principle of thermal protection of morphing mechanisms, the mechanical and control mechanisms of deformation, and the intrinsic law of parameter uncertainty on dynamic response and control accuracy, and solved the robust control problem of high-dimensional complex uncertain morphing mechanisms. The project "Research on Aerodynamic Principles and Structural Mechanics of Morphing Aircraft" combined the interdisciplinary knowledge and methods of aerodynamics, structural dynamics, and intelligent materials and structures to drive innovations in the following aspects: high-speed morphing aerodynamic concepts, nonconstant dynamic aerodynamic characteristics and modeling during deformation, flight mechanics modeling during deformation, shape memory alloy (SMA) intrinsic structure model, efficient drive design principles, and system dynamics.

From the perspective of plan implementation, the key projects were mainly carried out through a multidisciplinary integration approach. For example, the projects "Design and Environmental Response Mechanism of New Active–Passive Thermal Protection Structure for Scramjet Engine" and "Research on Actively

Cooled Ceramic Matrix Composites and Structures Thereof" involved interdisciplinary studies of engines, mechanics, high-temperature materials, physics, chemistry, and engineering thermal physics. The project "Construction and Experimental Validation of Hydrocarbon-Fueled Supersonic Combustion Mechanism" involved interdisciplinary studies of engines, chemistry, and fluid dynamics, and built a basic database of hydrocarbon fuel reaction and mechanism generation software. Projects such as "Theoretical Research on Design Optimization of Multifunctional Ultralight Structures for Near-Space Vehicles" and "Multifunctional Structure Research Integrating Power, Thermal Control, and Structure" designed and prepared ultralight lattice structures that not only had high structural efficiency but were also equipped with preliminary multifunctional properties such as load-bearing, thermal management, energy source, and wave absorption by interdisciplinarity of mechanics, material science, optimal design, engineering thermal physics, and electromagnetism. Through multidisciplinary integration of aerodynamics, control, and materials, the project "Control Principles of Stability and Maneuverability of Hypersonic Vehicles Based on a Class of Intelligent Structures" proposed new structural design principles and control methods for intelligent morphing hypersonic vehicles concerning super magnetostrictive intelligent structures.

(3) Interdisciplinarity of integrated projects

The launching of integrated projects aims to provide proactive guidelines for the results of fostering projects and key projects, enhance multidisciplinary integration, strengthen the top-level design, and achieve the purpose of "integration and promotion, and leap-forward development" in response to the key scientific issues and the major national needs to be broken through. By encouraging advantageous participants to actively demonstrate their advantages and submit applications, several integrated projects have been deployed at different levels to address key scientific issues and interdisciplinary areas to promote breakthroughs in key scientific issues and improve collaborative innovation capabilities. For example, the project "Research on Material–Structure Integration and Thermal Protection–Insulation Integration for Near-Space Hypersonic Vehicles" fully combined the interdisciplinary efforts in solid mechanics, aerothermodynamics, material science, engineering thermal physics, optimization theory and methods, and testing and simulation experiments, to explore an integrated design and comprehensive performance of thermal protection–insulation materials and structures. The project "Integrated Research on Hypersonic Combustion, Flow, and Heat Transfer" integrated the research results of inlet flow, fuel cracking and stable combustion, combustion and heat transfer, and combustion process control, and focused on exploring and integrating the design methods of combustion chamber optimization considering multiple factors such as thermal protection and efficient combustion. The project "Research on Attitude–Aerodynamic Coupling Mechanism and Coordinated Control of Near-Space Hypersonic Vehicles" integrated the research directions of flight control, mechanics, and aerodynamics, and focused on the design method of an adaptive coordinated control system of near-space hypersonic vehicles. The project "Multiparameter Experimental Integration Methods and Technologies for High-Temperature Thermal Protection

Materials and Structures in Ultra-High-Temperature Oxidation Environment" integrated material science, high-temperature solid mechanics theory, and experimental mechanics to explore high-temperature experimental mechanics methods and technologies for extreme environments, and enhanced the innovation capability of experimental methods and technologies for extreme environments, providing strong support for multiple fields, such as aerodynamics, propulsion, thermal protection, and structures. The project "Study of Aerodynamic/Propulsive/Structural Couplings of Hypersonic Vehicles" integrated the research results of flow, combustion, heat transfer, and structures, providing a theoretical basis for the integrated aerodynamic/propulsive/structural design of hypersonic vehicles. The project "Control-Oriented Near-Space Hypersonic Vehicle Dynamics Modeling and Verification" integrated the research on flight attitude, aerodynamic coupling mechanism, and coordinated control, and established a control-oriented hypersonic vehicle dynamics model with clear reliability by analyzing the aerodynamic characteristics in a near-space flight environment.

2 Research Circumstances

2.1 Overall Scientific Objectives

The Plan focuses on the scientific issues involved in the studies of mid-level (30–70 km above the ground) near-space hypersonic long-range maneuvering vehicles, and the overall scientific objectives are as follows:

(i) To develop innovative theories and methods for key fundamental scientific problems of near-space vehicles in frontier areas, so as to enhance China's international status at the forefront of research and enable us to form and develop related national technologies;
(ii) To make a breakthrough in the source innovation of technologies, improve China's independent innovation capability in related fields, and support the leapfrog development of related technologies;
(iii) To gather and develop a team of excellent research talents who stand at the international frontier and have the ability to innovate in theory and source technology, promote the establishment of several interdisciplinary basic research platforms in this field, and support the sustainable development of China's near-space vehicle technologies.

2.2 Key Scientific Issues

The key scientific issues to be addressed in the Plan and relevant projects are as follows.

(i) Aerodynamics in a near-space flight environment. The research focused on the coupling mechanism of high-temperature, nonequilibrium, viscous interaction, rarefied gas effect, and turbulence effect in near-space high-speed flight; the prediction method of aerodynamic characteristics; the mechanism of thermal environment prediction and thermal protection; and the principle and method of wide Mach number range maneuvering. Four project clusters were formed, i.e., "theories and modeling of near-space hypersonic aerodynamics," "hypersonic thermal environment prediction and testing technology," "aerodynamic layout principles of hypersonic vehicles," and "flight and control principles of hypersonic vehicles".

(ii) Advanced propulsion theories and methods. The research focused on the theories and methods of hypersonic combustion, the interaction between hypersonic flow and combustion, high-efficiency intake and exhaust integration, and fluid–solid coupling of thermal protection and thermal environments in combustion chambers, which strengthened the research of ground experimental simulation and flow field diagnosis methods and actively explored new propulsion principles and methods. Six project clusters were formed, i.e., "design methods and flow control of hypersonic inlets," "hypersonic combustion mechanism," "thermal protection of scramjet engine," "scramjet engine control," "new concept propulsion," and "measurement and testing technology".

(iii) Ultralight materials/structures, thermal environment prediction, and thermal protection. The research focused on lightweight/multifunctional materials and structures, ultra-high-temperature non-ablative materials and structures, integrated design and interdisciplinary optimization theories and methods, material response mechanisms in service environments, new material preparation and characterization methods, and other issues, which strengthened analytical and experimental methods and actively explored new active/passive combined thermal protection–insulation principles and mechanisms. Six project clusters were formed, i.e., "thermal–mechanical coupling mechanism and analysis methods," "lightweight multifunctional materials and structures," "high-temperature thermal protection–insulation materials," "high-temperature wave-transmitting materials," "material performance characterization and testing techniques," and "exploration of new materials and principles".

(iv) Intelligent autonomous control theories and methods for hypersonic vehicles. We developed a control-oriented vehicle dynamics modeling and verification method with a focus on the theories and methods of coordinated flight control of hypersonic vehicle stability and maneuverability, strong robust adaptive control that can adapt to a wide range of parameter changes, and structural dynamics analysis and control of hypersonic vehicles, which proactively explored the aerodynamic principles and control methods of morphing flight. Five project clusters were formed, i.e., "control problems of hypersonic waverider vehicles," "control problems of hypersonic gliding vehicles," "morphing hypersonic vehicles," "research on aerodynamics, elasticity, stability, and maneuverability of hypersonic vehicles," and "research on active monitoring of structural vibration and thermoelastic flutter control".

After repeated discussions by the Steering Committee of the Plan, eight key scientific issues requiring imminent breakthroughs were identified concerning the above four key scientific issues:

(i) Principles and methods of flight combining aerodynamic and centrifugal forces;
(ii) Principles and methods of thermal environment and non-ablative thermal protection for long-time near-space flight;
(iii) Mechanisms and methods of propulsion related to supersonic combustion;
(iv) Mechanisms and prediction methods of the coupling of high temperature, nonequilibrium, viscous interaction, rarefied gas effect, and turbulence effect;
(v) Experimental and numerical simulation theories and methods for near-space vehicle environments, as well as the coupling theory and methods of CFD and computational structural dynamics;
(vi) Ultralight multifunctional materials and new configurations and methods of material–structure integration and optimal design;
(vii) Principles and methods of the material thermal–force coupling response mechanism and thermal protection structural design;
(viii) Intelligent autonomous control theories, morphing flight principles, and flight control methods.

The solution of the above four key scientific issues is essential to fully achieving the objectives of the Plan. From the perspective of the process based on our knowledge, we should follow the layout approach of "aerodynamics first, power as the core, materials and structures as the foundation, and control as the key." From the perspective of development, to take leaps of near-space vehicle technologies, we also need to pay attention to the unified and interdisciplinary characteristics of the key scientific issues and promote the synergistic development of key technologies of near-space vehicles.

3 Significant Progress

The Plan aimed to solve the deep-seated problems in the development of China's near-space vehicles by conducting basic, forward-looking, and pioneering research on relevant basic scientific problems to meet the national defense demand. It has played a significant role in ensuring national security and the peaceful use of space.

Since the inception of the Plan nine years ago, the participants of the Plan have published 2,621 papers, including 1017 papers in international journals, 56 of which were published in AIAA (American Institute of Aeronautics and Astronautics), 646 papers in domestic journals, and 958 papers in national and international conferences. Among the papers published, 1081 were indexed by SCI (Science Citation

Index), 615 by EI (Engineering Index), and 127 by ISTP (Index to Scientific & Technical Proceedings). The total number of SCI citations of published papers exceeded 6,000. We applied for a total of 398 domestic patents, 270 of which were granted. We received eight second prizes of China's State Natural Science Awards, five second prizes of the State Technological Invention Awards, four International Academic Awards, as well as 12 first prizes and 10 second prizes of provincial and ministerial awards. Among the researchers, one was elected a CAS academician; one was elected a foreign academician of Russian Academy of Sciences; six were appointed as distinguished professors of "Changjiang Scholars Program"; seven were granted the National Science Fund for Distinguished Young Scholars; nine were granted by the Excellent Young Scientists Fund; and 10 were supported by the Program for New Century Excellent Talents in University of the Ministry of Education. We have organized 82 international conferences and 157 domestic conferences. We have delivered 150 keynote presentations in important international academic conferences and 192 keynote presentations in domestic conferences. We have cultivated 478 Ph.D. graduates, 731 M.S. graduates, and 50 postdoctoral fellows.

The Plan brought together a large group of research teams from universities and national defense institutes, greatly promoted the development and interdisciplinary studies of mechanics, physics, mathematics, material science, and information science, and facilitated interdisciplinary collaborative innovation and engineering application of research results. The substantive contributions of the Plan's achievements can be summarized as follows.

(i) New principles, concepts, methods, and technologies have been proposed, and important innovations have been achieved, which have enhanced the source innovation capability and raised the basic research level.
(ii) The plan has played an important role in supporting the development of major national engineering projects.
(iii) A group of high-level basic researchers and research teams have been gathered and cultivated, and scientific achievements with significant international impacts have been made.

China had a late start in the field of near-space vehicles, especially in the related basic research, and the technology accumulation was limited. There were no successful models or rich experiences to learn from. Therefore, to address the major strategic issue of developing near-space vehicles, we must take the path of independent and innovative development. To achieve leapfrog development of near-space vehicle research, a number of technologies in the four key scientific issues mentioned above must be solved. Since the inception of the Plan, important research progress has been made in the following aspects.

(1) Aerodynamics in a near-space flight environment

(i) The unsteady characteristics of separation flow under hypersonic conditions have been revealed. A new flow separation pattern starting from the limit cycle—the flow surface with a closed limit—has been discovered, and the 3D unsteady wall separation criterion for moving walls has been further improved. The flow measurement technology and results with high precision are of great value for theoretical analysis and verification of numerical simulation results. The new unsteady flow separation pattern lays a solid foundation for the study of the dynamic characteristics of near-space vehicles. It has been applied to the study of the separation flow characteristics of near-space vehicles, the study of the flow field characteristics inside and outside the nozzle of attitude control engines of near-space vehicles, and the study of the separation flow effects of various combinations of interceptor missiles.

(ii) The coupling mechanisms of high-altitude, high-temperature nonequilibrium effects and thin flow effects have been explored. Supplemented by the numerical validation of the direct simulation Monte Carlo (DSMC) method, the theoretical analysis of the model was mainly used to study the characteristics of the chemical nonequilibrium thin flow and the aerodynamic heating of the stagnation point on sharp leading edges and to develop an engineering theory for the nonequilibrium real gas effect coupled with the aerodynamic heating of the sharp leading edges by the rarefied gas effect, which is of an important referential value for the prediction of the aerodynamic characteristics of near-space hypersonic vehicles.

(iii) The compressible turbulence and transition mechanism at high altitudes were explored. The high-temperature real gas effects on typical hypersonic boundary layer flow were investigated based on the characteristics of near-space hypersonic flight, and the relationship between the location of the transition and the flow parameters was predicted, which is of a great referential value to the aerodynamic design and thermal protection of aircraft. Direct numerical simulations (DNSs) using the Tianhe-2 computer system were conducted, which are of great significance for research on the fine prediction of the frictional resistance of near-space hypersonic vehicles.

(iv) A new method for aerothermal testing of hypersonic vehicles was developed. Compared with the traditional single-point measuring method (heat-flux sensor), phosphorescent heatmap technology enriched the means of experimental research on the thermal environment of hypersonic wind tunnels, enabled the large-area high-precision measurement of the thermal environment of vehicles, increased the data volume by 1–2 orders of magnitude, and achieved leapfrog development in pulse wind tunnel tests. We studied key technologies, such as the optimization of phosphorescent materials, the dual-color phosphorescent heatmap system, and model material selection, developed high-performance single/dual-color phosphorescent materials, and thereby established a dual-color phosphorescent heatmap based on pulse wind tunnels. The phosphorescent heatmap has been applied to the thermal environment test prediction of several hypersonic models, and a large amount of surface measurement test data has been obtained, which clearly presented the heat flux distribution trend on the model surface and provided data support for the thermal protection design and optimization of relevant engineering models. These efforts were unanimously approved by the model application departments.

(v) An adaptive coupled calculation model for aerodynamic heating and thermal protection material was established. The integrated calculation method of thermal protection and aerodynamic heating was developed, taking into account the surface radiation characteristics, surface catalytic properties, and oxidative ablation of actual thermal protection materials, thereby providing critical technical support for the study of ablation characteristics of thermal protection materials used in the design of near-space hypersonic vehicles. The basic methods and tools for the computational analysis of the hypersonic thermal environment were improved, covering the effects of surface properties of complex materials, complex physical phenomena, and complex geometry on the thermal environment, and summarizing the variation laws. The results have already been applied to manned spaceflight and lunar exploration projects.

(vi) New flight principles and aerodynamic layout optimization methods were explored. Wind tunnel tests and numerical simulation verifications of the single-degree-of-freedom roll stability criterion of the vehicle were completed, and the study of similar criteria and test simulation methods of dynamic multi-degree-of-freedom wind tunnel test was conducted. A static stability design study of waveriders was carried out, and lateral-directional static stability was achieved through the modification of the windward surface. Experimental verification of the feasibility of active thermal control technology was conducted to reduce heat flux and drag by reconfiguring the flow field of the aircraft head. The hypersonic wind tunnel dynamic test technology can be used to test and verify the coupled pitch/roll motion characteristics of near-space vehicles under hypersonic conditions and provide assessment and verification data for numerical simulations, which has already been applied to the development of near-space vehicles and highly maneuverable missiles and has provided theoretical support to ensure stable maneuvering and control.

(2) Advanced propulsion theories and methods

(i) A new method was developed for hypersonic inlet design. The concept of curved compression was proposed to realize the reverse design required by the aerodynamic parameters of the inlet exit section or the compression surface, which proved the excellent aerodynamic performance of surface compression and provided a new method for the aerodynamic design of high-performance hypersonic inlet and exhaust systems. An integrated design method of the osculating inward turning cone waverider inlet was developed. A design method for special-shaped engine runner structures was developed from scratch, which laid an important foundation for the coupled efficient design of engine intake and exhaust systems as well as combustion chambers. The concepts of curved compression and curved compression intake channels have already been accepted by research institutes in China and have been used in the aerodynamic design of hypersonic intake channels.

(ii) The supersonic combustion mechanism was explored. The first automatic generation program and thermal and kinetic database for cracking and combustion reactions of hydrocarbon fuel were established in China. The first Chinese automatic generation software for the aviation fuel combustion mechanism was developed, which changed the status quo of China's combustion simulation by relying on foreign software and reaction mechanisms. The innovation capabilities of China in basic combustion research and aerospace engine design and application research were enhanced, laying an excellent foundation for advances in hypersonic technologies. A new method for online measurement of high-temperature thermophysical properties of aviation fuel was established; the chemical heat sink was scientifically defined; and the measuring method was established. The accurate measurement of pyrolysis gas density solved the problem of experimental measurement for the flow velocity of pyrolysis gas in the cooling channel at 750 °C and above. These measuring methods for high-temperature thermophysical properties have laid a foundation for tackling the key technologies in the active cooling design for scramjet engines.

(iii) The active/passive thermal protection mechanisms of the scramjet engines were explored. The new concept of double-pressure cracking for active cooling of scramjet engines was proposed to overcome the disadvantages of the supercritical active cooling methods widely adopted at home and abroad, which significantly improved the chemical heat sink and eliminated the bottleneck problem of fuel coking during high-temperature and high-pressure cracking. In 2014, the double-pressure cracking cooling plate passed the 750 °C long-term experimental verification and was called "a new breakthrough in hydrocarbon fuel active cooling technology" in a major special project research brief. Advancements have been made in the research of active cooling internal protection material systems, which further improved the database of C/SiC composite materials and enhanced relevant design capabilities. C/SiC-M composite materials with excellent high-temperature and ablation resistance were prepared, in which the passive thermal protection capability of C/SiC composite materials was significantly improved. The relevant results have already been applied to the development of the C/SiC composite thrust chamber. The mechanical properties and ablation resistance of the composite materials have been remarkably improved, which have significantly prolonged the service life and enhanced the reliability of the thrust chamber.

(iv) The mechanisms of detonation propagation and deflagration-to-detonation transition in supersonic flows were explored. A fine numerical simulation and experimental study of the hot jet detonation initiation and propagation of supersonic premixed gas was systematically conducted to verify the feasibility of hot jet direct initiation of supersonic premixed gas and clarify the hot jet initiation mechanism and propagation pattern of supersonic premixed gas. The hot jet initiation mechanism of supersonic premixed gas was revealed, and a finer 3D detonation wave structure was developed, which deepened our understanding of the physical process of detonation in supersonic flow and laid a solid foundation for the development of detonation theory in supersonic flow. A new mechanism of low-frequency combustion instability in scramjet engines was revealed, namely, low-frequency combustion oscillations caused by periodic back propagation of the flame.

(v) The modeling and control methods of scramjet engines were explored. The starting/nonstarting catastrophe mechanism in the inlet, the subcombustion-to-supercombustion mode transition mechanism, and the bifurcation mechanism of mode transition in the combustion chamber of a scramjet engine were explored, and a theoretical model was developed. A catastrophe control approach combining switching control and catastrophe mode transition control was proposed. From the perspective of engine control, the flow instability phenomenon was observed, and the geometry of the instability boundary in the engine flow instability process as well as the finite and strictly separable types of combustion chamber–inlet interaction of ramjet engines were analytically derived. A fast identification method of complex flow dynamic patterns based on deterministic learning theory was proposed, which can quickly determine the flow state of hypersonic inlets.

(vi) A low-cost flight test platform for near-space science and technology was successfully developed. This platform project was funded by the Plan and the major science and technology innovation project of the National University of Defense Technology, with the goal of successfully developing a low-cost flight test platform for near-space science and technology by the end of the 12th Five-Year Plan (2011–2015) and conducting related flight tests. On December 12, 2015, the platform successfully conducted its first flight test at the Jiuquan Satellite Launch Center, making it the second low-cost near-space hypersonic general-purpose flight test platform after the Hypersonic International Flight Research and Experimentation (HIFiRE) program, which was jointly developed by the U.S. and Australia. It can provide flight demonstration and verification capabilities for key technology research on China's scramjet engine and hypersonic flight vehicles, as well as a flight test research platform for China's basic science research in near space. It is also yet another successful demonstration of China's hypersonic researchers, who have been striving to enhance the independent innovation capability and thus climb to the peak of science and technology in the international arena.

(3) Ultralight materials/structures, thermal environment prediction and thermal protection

(i) The theories and methods for lightweight material and structural design were explored, and the theory of lightweight material–structure integrated design and design optimization of hierarchical structures were established. For structures composed of ultralight porous materials, we realized the coupling of two geometric scales of material/structure based on the progressive homogenization theory and then proposed, deepened, and expanded a porous anisotropic material with a penalization (PAMP) model with concurrent material/structure multiscale geometry. Furthermore, we established the theoretical framework as well as the mathematical formulation and numerical implementation techniques for the corresponding problems to achieve an optimal design of lightweight porous materials and structures with concurrent multiscale geometry. The computability of the concurrent multiscale material/structure optimization problem was significantly improved by solving the sensitivity transfer technique between different material/structure levels and breaking the limitation that the classical solid isotropic material with penalization (SIMP) model (for solid materials) cannot realize the topology optimization of structures constituted by porous materials. New manufacturing processes for 3D printing additive materials provided new opportunities for the development of this method, which was evaluated by international peers as an "important discovery" and an "interesting recent research." The proposed hierarchical optimization method has been applied to the lightweight structural design of the new-generation launch vehicle, which has been an important contribution to ensuring the launch capability of the vehicle.

(ii) The design methods of material–structure integration and thermal protection–insulation integration for near-space hypersonic vehicles were explored. The correlations between different material and structural properties were identified at both the material and structural levels; the influence of design factors on the overall performance of thermal protection was analyzed with the thermal protection–insulation properties of the material comprehensively considered; and integrated design and comprehensive performance analysis methods for thermal protection–insulation were established. The problems in the application of multiscale design and multiobjective optimization in material and structural design for thermal protection were studied. For the integrated structural/thermal protection scheme, a method of thermal–mechanical coupling optimization based on genetic algorithms and a method of thermal–mechanical coupling optimization design of thermal protection systems based on topology optimization were established. As a result, the cooperative mechanism and design method of thermal protection, mechanical transfer and load-bearing were developed, with thermal/mechanical matching taken into account. Based on the randomness of the existing service environment and material properties and with multiscale and uncertainty theories and methods introduced into the design, optimization, and evaluation of thermal protection materials and structures, a nondeterministic analysis method was developed. An optimal design method for thermal protection systems based on the reliability index was established with the failure probability and reliability sensitivity given, thereby providing strong support for the optimal design. The relevant results improved the reliability of the physical model and the integrity of the method in the transformation of the engineering development method from "separation and superposition" to "thermal–mechanical coupling," thereby providing strong technical support for the design of high-temperature thermal protection components of future national aerospace vehicles.

(iii) Multifield coupled material–structure testing techniques for near-space hypersonic vehicles were developed. The experimental techniques for key parameters including force, heat, and oxidation in the multifield coupled service environment were developed; a test system for mechanical properties of materials in vacuum (inert gas) environment at 2600 °C and a test system for thermal shock resistance of multifunctional materials in rapid temperature rising/falling were established. A pioneering method for the high-temperature optical measurement of film/substrate systems was developed to enable the measurement of surface morphology, deformation, and film stresses and reveal the nonuniform evolution of film (coating) stresses at high temperatures. Based on the developed measurement system, the thermal response and oxidative ablation behavior of typical high-temperature thermal protection materials for extreme environments were systematically investigated, and the temperature response and performance evolution laws were revealed. The strong coupling effect between the aerothermodynamic environment and the UHTC materials as well as the main control elements were discovered, and the critical state criteria for the transition from non-ablation to ablation were developed. Thus, the oxidation mechanism, performance prediction, and oxidation inhibition methods of UHTC materials were obtained. To meet the requirements for in-situ measurement of hot end components of near-space vehicles, we systematically studied the high-temperature optical deformation field measurement and independently developed a high-temperature mechanical test system to realize the structural-level visualization measurement of thermal protection systems for ground assessment. In response to the requirements for measurement of the key mechanical parameters of high-temperature thermal protection materials and structures in UHT environments, we proposed a new method for deformation field measurement of high-temperature optical coherence and incoherence and developed a new technology for deformation carrier systems to enable high-temperature deformation field measurement at 1550 °C. We developed a multifield coupled measurement technique in a hypersonic wind tunnel to measure model vibration, model deformation, and aerodynamic heating in hypersonic aeroelasticity experiments. We conducted a hypersonic airfoil flutter wind tunnel experiment to run subcritical flutter tests using a fixed Mach number and step-variable pressure technique for flat wing models of X-15 and identified the model flutter boundary using the flutter boundary function method. We explored the mechanism of hypersonic aeroelasticity and especially studied the influence of aerodynamic shape and aerodynamic heating on the flutter of rudder surfaces and multifield coupling characteristics, thereby developing a number of innovative test methods and techniques to deepen our understanding of the physical properties and mechanical behavior of materials and structures with hypersonic multifield coupling.

(iv) A design method for advanced concepts, including porous, grid, and lattice structures, was developed. The primary and secondary molding processes of composite lattice structures with independent intellectual property rights were established, and an all-carbon fiber composite lattice structure was successfully prepared, which laid the foundation for embedding micro devices and realizing multifunctionalization. Using the inlay process, two kinds of 2D lattice structures, namely, glass fiber and carbon fiber composites, were prepared, which showed ideal wave absorption characteristics within the range of 4–18 GHz according to the reflectivity test results. A mesostructure model of Voronoi metallic foams was established using X-ray tomography. Through the optimization of the freezing injection molding process, the control of the gradient pore structure and performance of YSZ porous ceramics was realized. Based on the principle of the "bionic gecko foot," carbon nanotubes were homogeneously grafted onto the surface of the ultrathin aluminum alloy liner, which increased the strength of the composite structure interface layer by 28%.

(v) New materials, concepts, principles, and methods for non-ablative thermal protection were explored. The optical properties of photonic crystals were used to regulate thermal radiation, and photonic crystal thermal protective coatings were designed and prepared. A new concept and method for enhancing the thermal shock resistance of ceramics by bionic design of ceramic surface structures were proposed. Through plasma etching and acid etching, superhydrophobic nanostructures on the surface of ceramics were successfully introduced to mimic the surface of dragonfly wings. During a thermal shock of ceramics, the ceramic surface after bionic treatment was automatically covered by an air film, which increased the thermal resistance of the ceramic surface by nearly 10,000 times and greatly improved the thermal shock resistance of the ceramic material. This achievement greatly expanded the traditional approaches to the study of thermal shock failure of ceramics and provided a new perspective for relevant research. to achieve the overall performance desired through microstructural design of the material surface. The process of forming C/C composite materials with high thermal conductivity (HTC) was explored at multiple levels and perspectives, and a series of processing technologies from melt spinning to bulk carbon fiber ribbon composites were proposed.

(4) Intelligent autonomous control theories and methods for hypersonic vehicles

(i) A new concept and method for fine attitude control of hypersonic waverider vehicles were proposed. The concept of fine attitude control of hypersonic waverider vehicles was proposed. The method for fine attitude control of hypersonic vehicles under conditions such as aeroelasticity and engine vibration was studied, which enriched the theory of hypersonic vehicle flight control and created an innovative new method of a fine attitude control system designed for hypersonic waverider vehicles.

(ii) A new concept and method for model migration of near-space hypersonic vehicles were proposed. The concept of model migration of near-space hypersonic vehicles was proposed. By transforming the migration of the vehicle dynamics model into the migration of the aerodynamic parameters in the model, we studied the similarity measurement factors and evaluation methods for the new aircraft and the base aircraft, as well as the start-up parameter migration methods for the new and base aircraft. A set of new methods based on model migration theories was developed for the dynamic modeling of near-space hypersonic vehicles, providing a new technical approach for the rapid modeling of hypersonic vehicles in the absence of experimental conditions.

(iii) A new concept and method of multichannel coordinated control for near-space hypersonic vehicles were proposed. The coupling characteristics between the control channels of the vehicle were studied in depth, and the coupling measures and decoupling/nondecoupling conditions between the control channels were identified. The idea of multichannel coordinated control of near-space hypersonic glide vehicles under nondecoupling conditions was proposed. The multichannel coordinated control method of near-space hypersonic glide vehicles under nondecoupling conditions was studied. The traditional vehicle design routine using the three-channel control system was broken, which has enriched the theories and methods of hypersonic vehicle flight control.

(iv) An initial investigation of the attitude–aerodynamic coupling mechanism of near-space hypersonic vehicles was carried out. Based on our in-depth study of the near-space flight environment, typical flight patterns of hypersonic vehicles, and possible flight envelopes, a measurement factor to characterize the coupling of flight attitude variables and aerodynamic parameters was proposed by studying the specific characteristics of the coupled flight attitude and aerodynamic forces. By using this measurement factor, the coupling of flight attitude variables and aerodynamic parameters of hypersonic vehicles under different flight conditions was quantitatively analyzed, and the special phenomenon of a sudden increase in such coupling at some critical points was found. In addition, two methods for describing the coupling of flight attitude variables and aerodynamic parameters were proposed, and the attitude–aerodynamic coupling mechanism of near-space hypersonic vehicles was initially explored, laying a foundation for the design of coordinated hypersonic vehicle control systems.

(v) A new idea for the integrated control of hypersonic waverider vehicles/engines was proposed. The acceleration-based integrated control framework was constructed by analyzing and utilizing the special characteristics of the acceleration variable, and the functions of the engine control system and vehicle control system were clearly defined. A control-oriented dual-mode ramjet engine model was developed to address the inlet unstart problem. The model was capable of characterizing the complex transition logic, hysteresis loops during switching, and parameter jumps that exist between supersonic combustion, subsonic combustion, and unstart through the analysis and realization of the mode switch logic. Based on the idea of scramjet engine thrust regulation/safety protection switching control design, a conservative dynamic performance index of the switching system was proposed, and a switching control system design method for this dynamic performance index was developed, which solved the problem that the traditional dynamic characteristics depended on the initial state at the time of switching and thus impeded the control design. A new concept and method of coordinated vehicle/engine control based on safety margins were proposed, which introduced a dynamic coordination factor based on the safety margin of vehicles and engines without changing the structure of the original flight control system, and this factor was used to coordinate the control between flight performance and flight safety.

(vi) An initial investigation of the dynamic time-varying law and mechanism of the unsteady aerodynamics of morphing aircraft was carried out. The possible aerodynamic layout of morphing aircraft for a wide range of velocities (subsonic, transonic, and hypersonic) was investigated. The unsteady aerodynamic characteristics of subsonic oblique wings and variable-sweep wings, transonic retractable wings and variable forward-sweep wings, hypersonic morphing osculating-cone waveriders, and oblique shock waverider configurations were explored from three aspects: aerodynamic layout design, circumferential flow calculation and experiment, and aerodynamic characteristics analysis. The phenomenon and mechanism of unsteady aerodynamic characteristics in the typical deformation process of morphing aircraft were discovered and revealed. The effective morphing aerodynamic layout and its aerodynamic characteristics in near space were identified for a wide range of velocities. In addition, new phenomena of 2D and 3D airfoils were explored via both theoretical analysis and wind tunnel experiments, and new explanations were given in terms of the mechanism. The hysteresis effect of dynamic aerodynamic characteristics in the deformation process was found, and the mechanism was revealed to be the "moving boundary" and "flow field hysteresis." The research achieved a subsonic–transonic–supersonic–hypersonic breakthrough in the study of dynamic time-varying law and mechanism of the unsteady aerodynamics for morphing aircraft.

Research in China and Abroad

Shanyi Du, Daining Fang, Haiyan Hu, Zhang Ren, Zhenguo Wang, Jing Fan, and Youda Ye

The daily life of humans depends on the utilization of time and space, and progress is made by knowledge and science. Since the beginning of the twenty-first century, society has entered the "era of big development," where new spaces such as the space, deep sea, and polar regions are being explored. Among these spaces, near space, which is an airspace that is very often traversed but rarely utilized, has become the focus of global strategic competition, demonstrating immeasurable development prospects and bringing unprecedented scientific and technological challenges.

Near space usually refers to the airspace above the flight altitudes of general aircraft and below the orbits of satellites in the altitude band of approximately 20–100 km, which has the environmental characteristics of thin air, smooth airflow, and abundant solar energy. Near-space vehicles refer to all types of vehicles that can make full use of such environmental characteristics and operate stably in near space. There are two main types of near-space vehicles: (i) low-speed or subsonic vehicles that leverage their large volumes to gain buoyancy or large airfoil to provide lift and feature a long flight, wide coverage, high altitude, and long endurance; (ii) supersonic or hypersonic vehicles with high lift and low drag aerodynamic profiles, which feature a long range, good maneuverability, and high hypersonic flight capability within the atmosphere. The U-2, SR-71, and other high-altitude strategic reconnaissance aircraft developed successfully in the 1960s by the U.S. have distinctive "near-space" characteristics [1–3]. In their decades of service, they have not only set a number of world records for human conquest of space but also played a key role during the Cold War owing to their high survivability, highly "blurred" rules of sovereignty, and remarkable effective performance. The reasons why near space has become a new strategic high point coveted by great and powerful nations are as follows. (i) It has obvious advantages in military effectiveness, and weapons and equipment that take full advantage of this space environment are expected to revolutionize multiple military capabilities. (ii) The rules of sovereignty are ambiguous; near space has not been systematically exploited; and there are no international laws and treaties defining whether this area belongs to airspace or space—whoever conquers this space first will have a greater initiative in future rule-making. (iii) There is great potential for civil

S. Du (ed.), *Key Basic Scientific Problems on Near-Space Vehicles*, Reports of China's Basic Research, https://doi.org/10.1007/978-981-19-8907-0_2

use, which, once realized, will have a huge impact on many existing industries and sectors and promote social and economic development for the benefit of mankind. (iv) There is a strong technological motivation since the conquest of near space means addressing various challenges in terms of cognition, methods, means, and concepts of science, technology, and engineering, which will have a great positive impact on the design, propulsion, energy, materials, structures, control, and effective load of vehicles, thereby promoting the accelerated development of related technologies.

Near space will provide an ideal pathway for hypersonic flight of long duration, high maneuverability, high efficiency, and reliability, which will make rapid long-range global reaching and rapid responding to time-sensitive targets possible while significantly improving the aerospace flight capabilities of human beings, such as cheap, reliable, and daily access to space, revolutionizing future military confrontations and people's lives, and becoming a strategic high point of international competition in aerospace in the twenty-first century.

1 Research Trends of Near-Space Vehicle Technologies Abroad

In the 1930s, Dr. Eugen Sänger proposed the concept of boost-glide trajectories and the design of Silverbird orbital bomber [4–6]. To overcome the weaknesses of ballistic missiles, QIAN Xuesen (Hsue-shen Tsien) proposed a boost-glide trajectory in the autumn of 1948, which uses a rocket boost to achieve the initial velocity and an aerodynamic configuration with a high lift-to-drag ratio to obtain the lift provided by the limited amount of air in near space to achieve long-range flight. This was named "QIAN Xuesen's Trajectory" [7, 8] (Fig. 1). On this basis, the U.S. carried out studies on various lifting-body hypersonic vehicles [9] (Fig. 2), conducted several flight tests, and actively transformed them into various weapon models. However, the potential of this concept could not be exploited owing to the limited technologies and capabilities at that time.

The relatively thin air in near space not only provides lift to reduce the aerodynamic drag and heat load but also provides the oxidizer for the propulsion system to increase the specific impulse. The concept of the scramjet engine emerged in the 1950s, as the U.S., Russia, and France worked on hypersonic cruise flight research. Years of effort and progress led to the creation and implementation of the U.S. National Aerospace Plane program. Despite a huge investment of 3 billion U.S. dollars and over a decade of research, the program was terminated owing to technical difficulties, the root cause of which was the failure to achieve breakthroughs in fundamental problems such as "scramjet performance" and "boundary layer transition" [10, 11].

In the twenty-first century, the U.S., supported by programs such as Falcon [12], Hyper-X [13–15], and HyTech [16, 17], especially driven by the National Aerospace Initiative jointly implemented by the U.S. Department of Defense and NASA in 2001 [18], was able to achieve breakthroughs in key hypersonic technologies, which

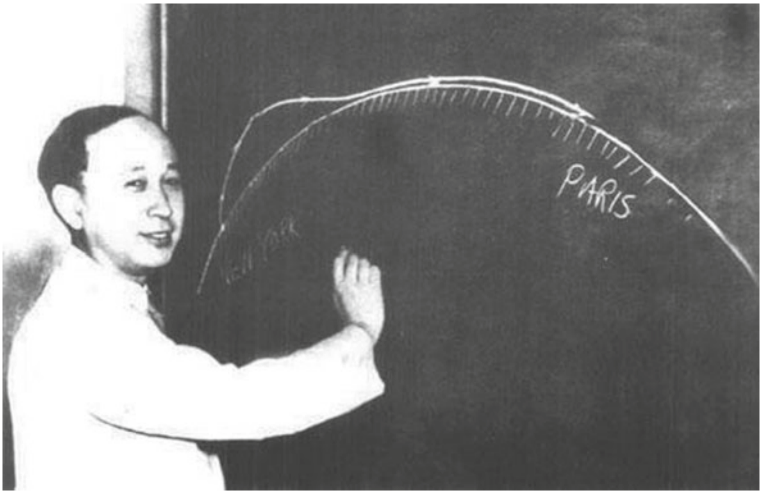

Fig. 1 Qian Xuesen and his trajectory

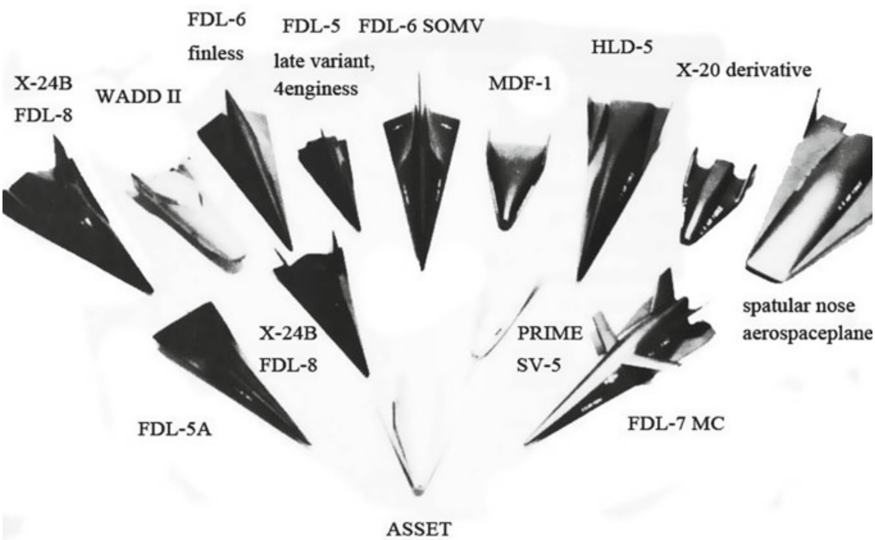

Fig. 2 Various configurations of lift bodies studied in the U.S. (1956–1966)

reinforced its confidence in conquering near space. HTV-2 is a major U.S. hypersonic technology validation program (Fig. 3), which aims to validate the key technologies of near-space hypersonic flight, such as aerodynamics, high-temperature materials and structures, and long-term high-precision methods, and to improve its mechanistic understanding of hypersonic flight [19, 20].

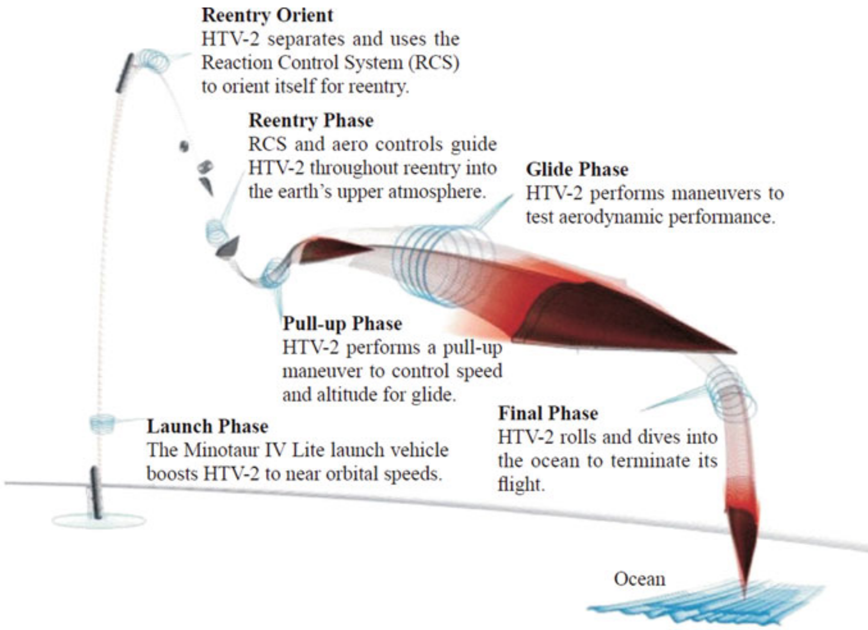

Fig. 3 Schematic of HTV-2 boost-glide trajectory

On April 22, 2010, the first flight test of HTV-2 achieved controlled flight above *Ma* 20 in the atmosphere but failed 9 min after launch [21]. The findings indicated that there was limited understanding of several aerodynamic aspects of the flight process, and it was announced that "we do not yet know how to achieve the desired control during the aerodynamic phase of flight. It is virtually an uncharted territory." On August 11, 2011, the second flight test solved the aerodynamic control problems of the first flight and reached a new stage of fully aerodynamically controlled flight at *Ma* 20 for 3 min, which validated the correctness of the transition prediction theory and model [22, 23]. However, there was an unexpected peeling of the C/C composite shell, which induced an unusual roll owing to shock waves, and the glide flight had to be aborted. DARPA believed that the two flight tests, although not completed, yielded a large amount of important actual flight test data for understanding aerodynamic control and material issues in *Ma* 20 flight conditions, which could be worth more than 40 years of ground simulations because only through actual flight can the understanding of the issues be significantly improved.

The AHW is a medium- and long-range hypersonic boost-glide vehicle that was supported by the U.S. Army (Fig. 4), designed and developed by Sandia National Laboratories (SNL), and inherited from many of the laboratory's earlier research findings on maneuverable reentry vehicles. On November 17, 2011, the first flight test of AHW was successfully completed. SNL therefore collected a large amount of flight data, assessed a number of key technologies, such as aerodynamics and thermal protection technology, verified the calculation model, and improved the reliability

Fig. 4 Schematic of AHW

of the numerical simulation [24]. On August 25, 2014, the second flight test was terminated early owing to an anomaly only 4 s after launch [25, 26].

Hypersonic cruise vehicles have been hailed as the third revolution in the history of world aviation after propeller and jet aircraft. Based on the HyTech program, the U.S. Air Force, DARPA, and NASA jointly implemented the X-51A flight test program [27]. The development of air-breathing hypersonic propulsion is shown in Fig. 5 [28].

In May 2010, X-51A made its first flight with a scramjet engine operating normally for 140 s, which was the longest operating time ever achieved by such an engine in a real flight at that time. At this point, the flight took an important step toward engineering and practicality. In June 2011, the second flight test failed owing to an inlet unstart; and in August 2012, the third flight test failed owing to the unexpected unlocking of the upper right control fin in the cruise stage, which was a large blow to the hypersonic cruise that had just seen hope. On May 1, 2013, X-51A conducted its fourth and final flight test, with the engine operating for 210 s, where the vehicle was accelerated from *Ma* 4.8 to 5.1, finally demonstrating the feasibility of hypersonic flight powered by a scramjet engine with endothermic fuels [10, 29].

Bearing the high hopes of the U.S., HTV-2's two flights that both ended up failing served as a sobering reminder of the difficulty of intercontinental boost-glide flight, and the postflight investigation report recommended not only obtaining technical experience from the second flight to improve the design tools and methods for the high-temperature composite aerodynamic shell but also comprehensively considering how to understand aerodynamic heating, how to grasp the material characteristics, the uncertainty, and variables, and how to predict the thermal strain and response though modeling and simulation. In 2012, DARPA proposed a follow-up integrated hypersonic program to develop, refine, and test next-generation technologies for worldwide *Ma* 20 + hypersonic flight [30, 31]. However, based on the success of AHW and X-51, which launched hypersonic flight into a new era, the U.S. Air Force

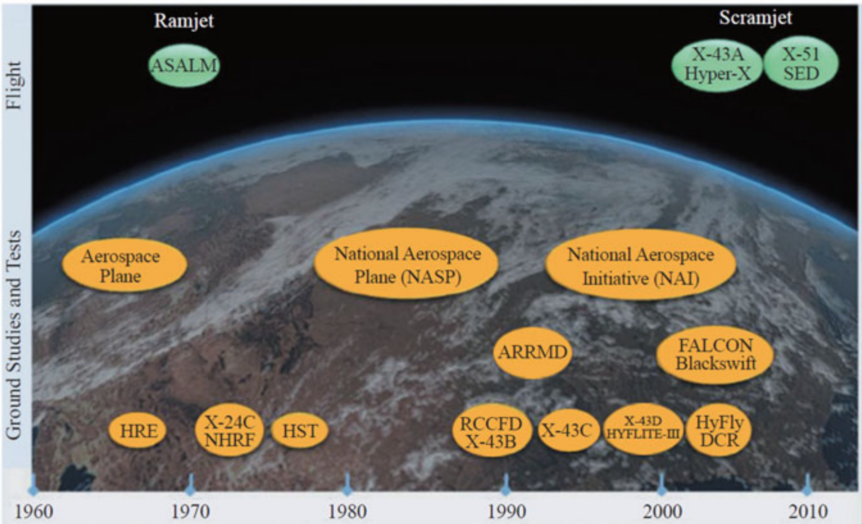

Fig. 5 History of aspirated hypersonic propulsion

proposed a phased development strategy for investing in air-breathing hypersonic technology, with the short-term focus on high survivability and time-sensitive strike capabilities and the long-term development of a cross-region intelligence, surveillance, reconnaissance and strike platform. The High Speed Strike Weapon (HSSW) program [32, 33], proposed in 2012, aimed to develop a demonstration weapon above *Ma* 5, using technologies such as modeling and simulation, scramjet engines, high-temperature resistant materials, GNC (guidance, navigation, and control), guidance heads and their antennas, warheads and their subsystems, thermal protection and thermal management, manufacturing processes, and small boosters.

In 2014, DARPA proposed two development programs, Tactical Boost Glide (TBG) and Hypersonic Air-Breathing Weapon Concept (HAWC) [10, 34–37] (Fig. 6), with the hope of being capable of hypersonic strikes in tactical ranges by 2025. TBG is a joint effort between DARPA and the U.S. Air Force to develop and demonstrate the technologies required for future hypersonic boost-glide systems in the air-launched tactical domain. These technologies mainly include vehicle concept solutions; aerodynamic/thermal characteristics (maneuverability and robustness) of large operational flight envelopes; system characteristics and subsystem composition for survivability and lethality in an operational environment; methods to reduce the cost and increase the affordability of demonstration and future operational systems; methods for thermal structural material maturity, structural design optimization, and affordable manufacturing; adaptive, robust guidance control techniques and real-time trajectory optimization techniques subject to high constraints; and techniques and devices capable of acquiring information about the aerodynamic environment and the thermal response of the shell. HAWC, also jointly implemented by DARPA and the U.S. Air Force, is designed to demonstrate key technologies for efficient and affordable air-launched hypersonic cruise missiles. These technologies include advanced hypersonic vehicle layouts, hydrocarbon-fueled scramjet engine propulsion systems, thermal management systems, affordable system design and manufacturing methods, efficient aerodynamic configurations for hypersonic flight, hydrocarbon fuel propulsion for sustainable hypersonic cruise, thermal management methods for high-temperature cruise, and affordable vehicle system design and manufacturing methods. These technologies will be further extended to reusable hypersonic vehicles for global reach and space transportation. In partnership with DARPA, the HSSW program will conduct two comprehensive technology validations in parallel: (i) tactical validation of air-breathing missiles to ensure that the missile is compatible with the 5th generation aircraft and can be carried internally by a B-2 or externally by an F-35; (ii) development and validation of rapid long-range strike capability through the TBG program.

Increasing aircraft speed has always been the relentless pursuit of humankind, and the horizontal takeoff of reusable hypersonic vehicles faces formidable technical challenges. The U.S. Air Force hoped to further improve the intelligence, surveillance, and reconnaissance (ISR) capabilities and the survivability of strategic reconnaissance aircraft using hypersonic technologies and explicitly proposed the development of hypersonic weapons and high-speed reusable vehicles in parallel by taking a three-step approach to developing hypersonic aircraft from proof-of-concept aircraft to short-life aircraft and long-life aircraft. Based on the breakthroughs in key technologies for small-scale scramjet engines, key technologies for large-scale combined-cycle propulsion systems are being developed, with the hope of developing global rapid response ISR capabilities and precision strike integration capabilities to take the lead in the increasingly violent area denial and counter-intervention confrontations. In November 2013, Lockheed Martin announced that it had found a solution to the thrust gap between turbine and ramjet engines, and on the birth date of SR-71, plans for SR-72 (Fig. 7) were revealed, with a designed cruising speed at *Ma* 6 [35, 38–40]. In 2014, NASA supported Rocketdyne and Lockheed Martin in

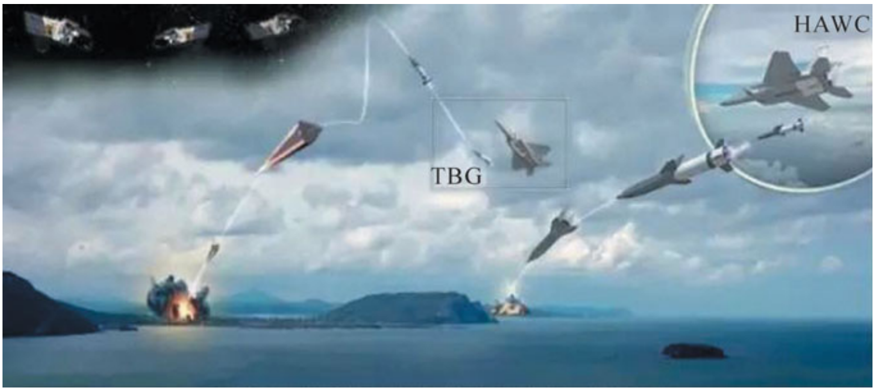

Fig. 6 TBG and HAWC

Fig. 7 Sketch of SR-72

the development of the SR-72 aircraft, hoping to develop a reusable, short-lifecycle hypersonic aircraft for tactical strikes and ISR missions by 2030 and to achieve long-lasting reusability by 2040.

In 2013, based on the urgent need for future access to space with low cost and rapid response, DARPA issued the solicitation and specific parameter requirements of the XS-1 experimental spaceplane program [41–43] with the aim of developing a reusable unmanned launcher with a cost, operation, and reliability similar to a modern aircraft, which is capable of launching small payload satellites into low Earth orbit (LEO) (Fig. 8). The reusable first stage of XS-1 should be capable of flying at hypersonic speeds at suborbital altitudes and returning to the ground, with the upper stage delivering the satellite into LEO. Key technical specifications include 10 flights in 10 days, a maximum flight speed above *Ma* 10 and the launch of a typical small payload into orbit, and a reduction in the cost to less than 5 million U.S. dollars for launching a 3000–5000-pound payload into space.

Europe has been focusing on key hypersonic technologies and fundamental research, and the following two projects have made breakthroughs in recent years. The Intermediate eXperimental Vehicle (IXV) is a European Space Agency (ESA) experimental suborbital reentry vehicle [44, 45]. IXV has a length of 5 m, a height of 1.5 m, a width of 2.2 m, and a launch weight of approximately 1.85 t. It has a lifting-body design, much like a scaled-down U.S. spacecraft, with advanced aerodynamic characteristics and a sophisticated GNC system that allows for good maneuverability during atmospheric reentry using aerodynamic control surfaces.

On February 11, 2015, IXV [46] was launched at the Kourou Space Center in French Guiana by a Vega launcher to an altitude of 320 km and continued to climb to 412 km after separation to begin reentry, reaching a speed of 7.7 km/s at an altitude of 120 km and carrying more than 300 sensors to collect data on temperature, pressure, load, and aerothermodynamics. After a flight of approximately 100 min, it opened its parachute and splashed down in the Pacific Ocean, opening a new chapter in the development of ESA's atmospheric reentry technology and reusable spacecraft.

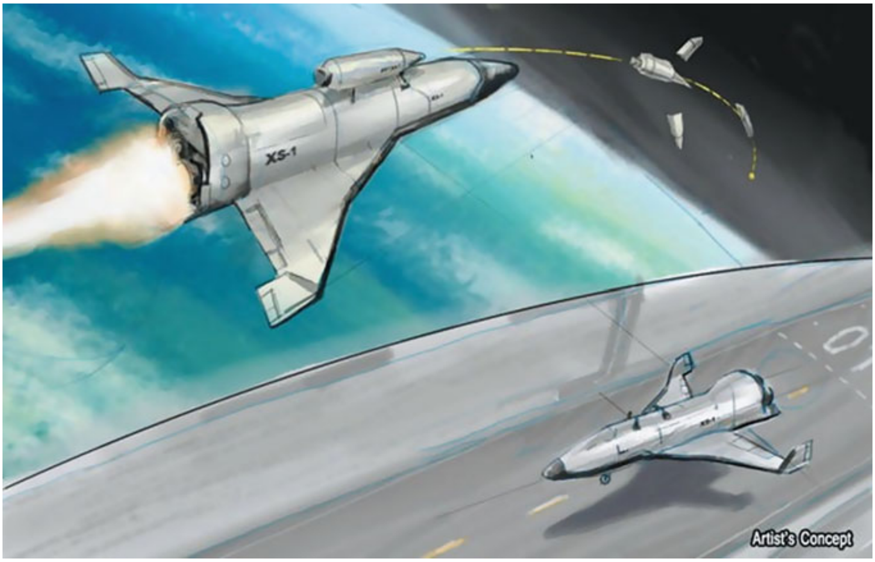

Fig. 8 Sketch of XS-1

The British company REL invented the Synergetic Air-Breathing Rocket Engine (SABRE) [35, 47–49], which was described as the greatest breakthrough in aerospace propulsion since the invention of the jet engine. The internal structure of SABRE is shown in Fig. 9. SABRE can operate in both air-breathing and rocket modes by organically combining jet turbine and rocket technologies to power aerospace flight. Its innovative precooler technology cools the incoming flow from 1000 to −150 °C in 0.01 s and solves the frost problem by injecting methanol. This key technology was successfully verified in 2012. In November 2015, the British defense contractor BAE Systems announced plans to invest approximately 31.7 million U.S. dollars to develop a hybrid rocket engine with REL and to begin ground testing of a 1/4 scaled-down SABRE demonstrator by 2020. The thrust range is expected to be adjustable from 20 t in air-breathing mode to 80 t in rocket mode. The initial design of Skylon, a SABRE-based reusable single-stage-to-orbit spaceplane, is now completed, while the SABRE engine and associated technologies can be further used on a variety of aerospace vehicles (e.g., hypersonic airliners). BAE Systems demonstrated a potential military application scenario for a *Ma* 5 air-breathing hypersonic platform at Air Show 2016.

Recently, Russia has become active again in the international hypersonic arena. Zircon, a hypersonic cruise missile developed by Russia [50], had its first flight test conducted in March 2016 using a ground-based launcher. Meanwhile, Russia has been working on the Yu-71 hypersonic glide vehicle for many years. Yu-71, known as a continuation of Project 4202, has been kept under high secrecy, and after the flight test in 2004, the Russian military announced that the warhead can change altitudes and directions to maneuver and fly in a way that anti-missile systems are powerless against it. In February 2015 and April 2016, Yu-71 made back-to-back

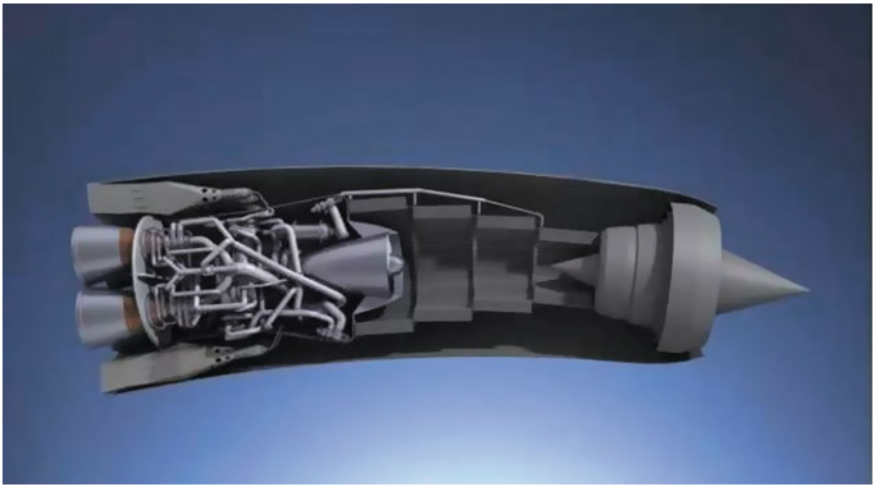

Fig. 9 Internal structure of SABRE

test flights, attracting widespread international attention. The flight tests were based on a highly maneuverable warhead with a high lift-to-drag ratio lifting-body design and carried out on an SS-19 ICBM (intercontinental ballistic missile), which was launched from Dombarovsky Air Base in eastern Russia.

2 Basic Research on Near-Space Hypersonic Technologies Abroad

In regard to hypersonic technologies, apart from their revolutionary, disruptive, and game-changing significance, people generally believe that hypersonic flight in the atmosphere is the most complex and dangerous flight area. After more than half a century of hard work, hypersonic technologies have not yet come to fruition. The fundamental reason for this is the lack of understanding of basic issues such as hypersonic gas dynamics, hypersonic air-breathing propulsion, and high-temperature materials and structures. In particular, along with the ups and downs of projects, related basic research has not been continuously supported.

NASA launched the Fundamental Aeronautics Program (FAP) in 2006 [51], in which hypersonic technology was one of the four major directions, aiming to lay a foundation for the development of a wider range of enabling technologies for air-breathing space entry and massive interplanetary reentry vehicles, with a focus on two-stage-to-orbit air-breathing propulsion technologies, lightweight reusable integrated airframes and propulsion structures, and physically validated and integrated interdisciplinary design tools (Fig. 10).

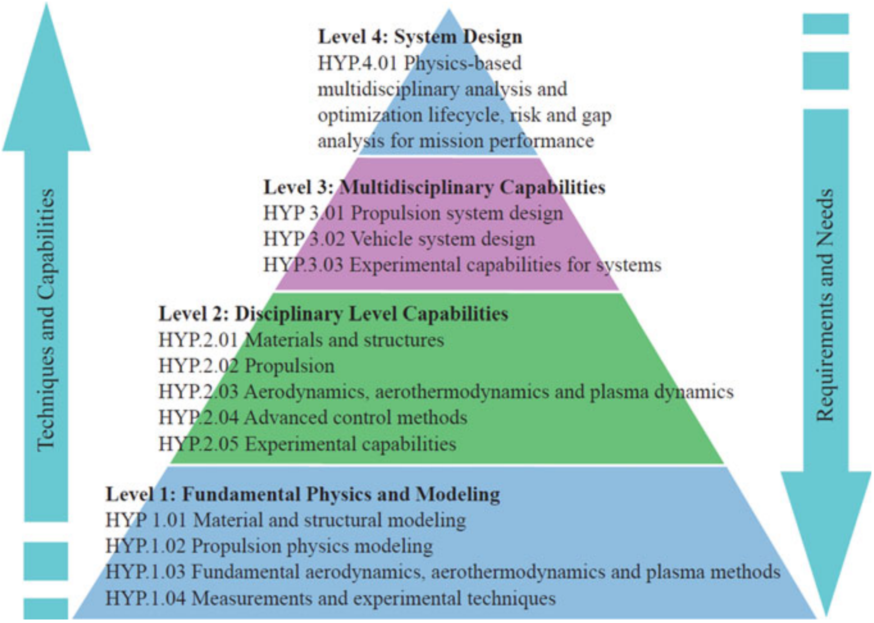

Fig. 10 Hypersonic research projects in FAP

FAP conducted research on the Large Scramjet Engine Test Technology (LSETT) and developed a design method for truncated-length internal rotating inlets with similar performance to full-size inlets. For turbine-based combined-cycle engine technology, the program invested the inlet performance and service characteristics, mode transition and associated inlet dynamics, as well as control strategies that ensured smooth inlet start and smooth mode transition. System simulation experiments were conducted by integrating the scramjet engine with the turbine engine and nozzle. For the reusable airframe and thermal protection system, the bonding and mechanical connection methods between the thermal insulation body and the main bearing structure of the vehicle were studied; the performance of the space shuttle thermal insulation tile/felt system was improved; a design method of a metal or ceramic matrix composite (CMC) support thermal protection system with thermal protection separated from the main structure was developed; a load-bearing thermal protection system with both mechanical and thermal load-bearing capacity that can share the mechanical load with the main structure was designed; and a flat plate prototype for flight load testing was prepared. For CMC materials, studies of modeling and analysis methods were carried out to continuously improve the modeling and physical understanding of CMC behavior, as well as durability and extend service life. Research on design methods for two-stage-to-orbit air-breathing vehicles has led to the development of interdisciplinary analysis and optimization tools, including integrated design and engineering analysis environments, high-reliability propulsion, and vehicle analysis methods.

In 2008, the U.S. Department of Defense launched the National Hypersonic Foundational Research Plan (NHFRP) [52] jointly with the U.S. Air Force, NASA, and SNL. The research involved modeling and simulation of the aerothermodynamic environment around the vehicle, design methods for high-temperature materials, and modeling and control of complex interactions between the vehicle surface and the surrounding flow field environment, aiming to provide a fundamental understanding for additional technical, systemic studies, or physical phenomena. NHFRP focused on six scientific fields critical and unique to hypersonic flight, including supersonic combustion, boundary layer physics, shock-dominated flows, nonequilibrium flows, environment and material interactions, as well as high-temperature materials and structures. In addition, NHFRP identified short-term (2010), medium-term (2020), and long-term (2030) scientific goals for each key field [52] (Table 1).

Science-driven flight data are very useful for understanding key physical phenomena under actual flight conditions and providing an important basis for validating ground tests and numerical simulation results and extrapolating to flight conditions. Considering that some large flight tests focus on a single demonstration of the technology concept with little opportunity to gain new scientific insights from the final flight data, in 2005, the U.S. and Australia jointly implemented the HIFiRE program, planning to collect scientific data through nine flight tests [53] (Table 2) to address a wide range of hypersonic conditions. Among those tests, HIFiRE-1, HIFiRE-2, and HIFiRE-3 were successful; HIFiRE-5 failed to achieve the designed test Mach number owing to an abnormal propulsion system failure but still provided flight data outside of the expected test window.

In August 2014, the HIFiRE program was modified, with HIFiRE-7, HIFiRE-5B, HIFiRE-4, HIFiRE-6, and HIFiRE-8 scheduled to be completed within two years, and the launch of HIFiRE-8 marking the end of the first phase of the HIFiRE program. The launch of phase two of HIFiRE was scheduled for 2015, with the plan to continue for eight years, aiming to provide the U.S. and Australian air forces with decisive and rapid-response tactical capabilities by 2024. In fact, as of December 2019, only HIFiRE-7, HIFiRE-5B, and HIFiRE-4 had been flight-tested. In March 2015, HIFiRE-7 was flight-tested at Andøya Space in Norway, where the effective payload accelerated beyond *Ma* 7 and the scramjet engine became operational after suborbital flight and reentry. During reentry, the ground station did not receive telemetry signals during the end-of-flight test window, and the flight data stream from the payload was lost for exactly 15 s. The chief scientist said, “Although the full dataset was not received, most of the new technology worked perfectly.” In May 2016, the HIFiRE-5B flight experiment in southern Australia was successfully completed, where the vehicle reached a maximum altitude of 278 km and a maximum speed of *Ma* 7.5. In July 2017, HIFiRE-4 successfully flew at the Woomera Range in southern Australia, reaching a maximum speed of *Ma* 8. As reported by the *Aviation Week Network*, the test vehicle lost contact with the ground soon after separation from the sounding rocket and failed to complete its intended test mission as planned.

The U.S. Air Force Office of Scientific Research (AFOSR) oversees basic research in the U.S. Air Force, and its mission to invest in basic research, is to discover, shape, and support the fundamental sciences that will profoundly impact the future of the

Table 1 Short-, medium-, and long-term scientific goals for relevant scientific fields in NHFRP

Scientific field	Short-term goals (to 2010)	Medium-term goals (to 2020)	Long-term goals (to 2030)
Supersonic combustion	• Simultaneous diagnostic measurements • RANS-LES of combustor components • Thermal control	• On-board diagnostics • Full-size combustor LES • External burning aerodynamic control	• Component DNS • Full-scale ground-flight tests • Fault-tolerant control
Boundary layer physics	• Semi-empirical transition estimation for mild 3D flows • Influence of flow chemistry on turbulence	• Semi-empirical estimation for a highly blunt cone or a cone with an angle of attack • Surface effect quantization • Deformation, active/passive flow control	• Physics-based numerical simulation of transition for actual systems • Flow control for boundary hierarchical optimization
Shock-dominated flows	• To define canonical experiments to validate simulations • To promote hypersonic LES and DNS to advance understanding transition, turbulence, gas–surface interactions, and aerodynamics in shock-dominated flows	• To define, prioritize, and execute new canonical experiments for validation • To mature simulation capabilities across Knudsen range including LES and high-temperature effects of radiation and ablation with automated grid adaptation	• To maintain standardization and flexibility of required simulation tests • To mature multi-physics simulation capabilities with quantifiable uncertainties including aerodynamics and material coupling
Nonequilibrium flows	• To identify critical reactions or components, and measure key cross-section • To identify new high-temperature reaction pathways including intermediate constants • To quantify regimes required by dynamic methods	• To identify high-temperature reaction and relaxation rates • To complete collisional-radiative model for nonequilibrium radiative heat transfer • Fast CFD/kinetic/hybrid 3D simulation tools concerning complex effects	• To complete multi-temperature and state-to-state reaction/relaxation models for gases of interest over full temperature range • Flight data and relevant ground test data with sufficient detail to validate models and tools

(continued)

Table 1 (continued)

Scientific field	Short-term goals (to 2010)	Medium-term goals (to 2020)	Long-term goals (to 2030)
Environment and material interactions	• To integrate general finite-rate surface chemistry into CFD codes or into loosely coupled equilibrium CFD with ablative material response • Millisecond surface evaluation	• In-situ surface composition and flux measurements • Validated surface chemical models • Fully coupled nonequilibrium CFD and material response	• Fully coupled, time-accurate boundary layer material response prediction • Engineered environment and material interactions for enhanced performance
High-temperature materials and structures	• To develop lab-scale test methodology to simulate flight conditions • To identify test methods to accelerate screening and validation • To develop in-situ characterization techniques	• To develop experimental techniques for complex UHT composites with tailored structures • To develop techniques to predict UHT properties from minimal samples at room temperature	• To optimize tools to predict material response and performance across scales • To develop coupled multiscale simulation techniques of material response to extreme environments and loads

Air Force. The AFOSR has recently funded many projects closely related to hypersonics; established collaborations between the Air Force and universities; sought revolutionary scientific breakthroughs by funding individual universities; attracted top researchers through the Multidisciplinary University Research Initiative (MURI) program to encourage high-threshold, high-level, multidisciplinary collaborations; and developed university–business partnerships and accelerated technological innovation through the Small Business Technology Transfer (STTR) program. In the area of hypersonics and turbulent flows, the focus is on "aerothermodynamics" and "turbulence and transition." The goal of aerothermodynamics is to identify, model, and explore key physical phenomena in turbulent and high-speed flows, with an emphasis on energy conversion and a focus on shock-dominant flows, nonequilibrium flows, and air–surface interactions. The goal of turbulence and transition is to develop a fundamental fluid physics knowledge base for future needs, with an emphasis on transition instabilities, sensibility, roughness effects, and jet bursts, and a focus on boundary layer physics, turbulence fundamentals, sensibility, and instability. In the area of low-density materials, the focus is on advanced material technologies that can significantly reduce system weight while continuously enhancing its performance and functionality, i.e., improving specific performances through structurally lightweight, multifunctional design materials in the scientific fields of materials synthesis and advanced processes, composites and hybrids, nanostructured materials, interface effects, multiscale materials modeling, and design materials. It is

Table 2 Main missions and scientific goals of the HIFiRE flight tests

Scientific field	HIFiRE-1 U.S	HIFiRE-2 U.S	HIFiRE-3 AUS	HIFiRE-4 AUS	HIFiRE-5 U.S	HIFiRE-6 U.S	HIFiRE-7 AU	HIFiRE-8 AUS	HIFiRE-9 U.S
Aerodynamics	BLT SBLT			Flight mechanics, separation and reentry	BLT			Continuous flight	BLT, flow fields, and interactions of shock waves
Propulsion		HCSJ @*Ma* 8	SJ fuel and combustion			Dual-mode HCSJ	SJ thrust measurement	SJ jobs	Dual-mode HCSJ
Stability and control	IMU assessment	Controlled depressed flight		Controlled suppressed flight		Controlled depressed flight			IAG&C
Materials and structures		Material survivability			Material survivability	Material survivability			Material survivability
Sensors					GPS/AO/MC				GPS/AO/MC
Instruments and measurements	TDLAS	OMC	OMC			OMC			
Effective payload	Cone cylinder	Scramjet engine	HyShot engine	Lifting body	E-cone	Scramjet engine	Scramjet engine	TBD	TBD
Trajectory	Guided	Guided	Guided	Unguided	Guided	Guided	Unguided	Unguided	Unguided

hoped that further weight reduction will be achieved based on traditional composite materials, that bottom-up material design methods will be developed to optimize performance in relation to specific needs, and that the system weight will be reduced by designing materials coupled with more structures and functions. In the area of aerospace materials for extreme environments, the discovery and characterization of materials that can withstand extreme environments will lead to fundamental knowledge that will enhance future revolutionary advances of the Air Force. The related studies include theoretical and computational tools for the discovery of new materials, e.g., ceramics, metals, and hybrid materials (composites); mathematics for predicting quantitative microstructures in material science, physics, and chemistry for materials in high-strength environments; and experimental and computational tools for complex combinations of loads in extreme environments. Especially for the extreme service conditions caused by the aerodynamic loads and propulsion systems of hypersonic vehicles, using refractory metal compounds such as zirconium and hafnium, the reusable temperature limit of the "silicon-based passive oxidation mechanism" can be broken. The coupling mechanism between the service environment and material response is considered, focusing on the far-from-equilibrium states, surface damage, damage with energy rate changes, and dynamic interfaces of materials.

To further advance basic hypersonic research, the U.S. Air Force and NASA jointly established three national hypersonic science centers in 2009 to support basic science and applied research and improve their understanding of hypersonic flight. (i) The National Center for Hypersonic Combined Cycle Propulsion is led by the University of Virginia, in collaboration with the University of Pittsburgh, George Washington University, Cornell University, Stanford University, Michigan State University, State University of New York, North Carolina State University, Alliant GASL, the National Institute of Standards and Technology, and the Boeing Company. The center brought together outstanding researchers who specialized in high-speed reactive flow modeling to develop advanced computational models and simulation tools for predicting the physical properties of combined cycle flows. The Center's unique equipment and advanced flow field diagnosis provide detailed data sets for developing and validating models of the physical properties of combined circulation flows. The joint efforts of modeling specialists and experimenters have contributed to the understanding of typical mode transitions and supersonic/hypersonic flow states for combined cycle propulsion, and to the resolution of common problems in hypersonic combined propulsion systems, with the effect of teamwork far exceeding the results of individual studies. (ii) The National Hypersonic Science Center for Materials and Structures is led by Teledyne Science and Imaging, Inc., and has brought together UC Santa Barbara, the University of Colorado, the University of Miami, Princeton University, Missouri University of Science and Technology, UC Berkeley, and the University of Texas at Arlington, to create a network that allows for full interdisciplinary and collaborative work, with the hope of revolutionizing hypersonic propulsion by creating new hybrid materials. Basic science studies include new methods for combining different materials in specific structures, new experimental methods for visualizing material performance control mechanisms, and models that can simulate these mechanisms with high reliability at different scales. New engineering sciences include the new methods for networked processes and the integration of experimental and scaled models into a realistic test system that will change the way materials are designed and verified. (iii) The National Center for Hypersonic Laminar–Turbulent Transition is led by Texas A&M University, in collaboration with California Institute of Technology, the University of Arizona, UCLA, and Case Western Reserve University, with hopes of extending and enhancing relevant hypersonic physical properties, identifying theoretical frameworks for major instability types across the domain, and providing comprehensive validation of the theoretical frameworks through fundamental stability tests while developing and validating strategies for transition control. The main work is to investigate the unsteady mode competition, sensitivity, and effects owing to thermochemical nonequilibrium, surface chemistry, cutting, and surface roughness. These issues are interconnected and integrated through a predictive and control system scheme.

3 Development of Near-Space Hypersonic Vehicles in China

The development of near-space hypersonic vehicle technologies in China mainly relies on our national security and interests, demand for sustainable national economic development, and drivers of scientific exploration and technological development. Since the 9th Five-Year Plan (1996–2000), China has been conducting exploratory and frontier research on manned spaceflight and hypersonic technology. With the continuous improvement of its comprehensive national power and rapid development of its economy, science, and technology, China has gradually increased its attention and investment in hypersonics. Since the start of the twenty-first century, the strategic role of near-space hypersonic technology has become increasingly prominent; the national demand has become increasingly stronger; and the role of basic research has become increasingly critical. In 2006, the State Council of China released the "Outline of the National Medium- and Long-Term Science and Technology Development Program (2006–2020)," clearly proposing that defense science and technology will provide support for safeguarding national security. In the section "Major mechanical issues in aeronautics and space science," which is one of the 18 basic scientific issues, it was proposed that priorities shall be placed on studying the mechanical issues involving supersonic propulsion systems and super high-speed collision; multidimensional propulsion systems and theory of complex movement control; theory of compressible turbulent flows; high-temperature thermodynamics; magnetic fluid and plasma dynamics; microfluid and microsystem dynamics; and structural dynamics of new materials. Simultaneously, a number of major national projects or science and technology projects closely related to near-space vehicle technologies were launched, which not only included key technology research and flight demonstration tests but also covered basic research and frontier explorations.

On January 13, 2014, the Washington Free Beacon reported that on January 9, China conducted the first test of a hypersonic glide vehicle, named WU-14. On

January 15, the Ministry of National Defense of China responded, “It is perfectly normal that we are conducting planned scientific research within our borders. It is not targeted at any country or specific target.” Since then, foreign media have successively reported that China conducted its second to seventh flight tests on June 7, August 7, and December 2, 2014, August 20 and November 23, 2015, and April 27, 2016, noting that the fourth flight test demonstrated “strong maneuverability” of the aircraft, that the fifth flight test rehearsed maneuvering to avoid interception for the first time, and that after the sixth flight test the vehicle had the designation “DF-ZF.” The vehicle conducted seven consecutive flight tests in more than two years, which drew a great deal of attention from the world, with foreign commentators saying, “it is not often that the same vehicle is tested so frequently, which may reflect China’s expectations for this revolutionary new type of vehicle,” “it indicates that China places a high priority on the development of this weapon, which may reflect Chinese expectations for this revolutionary new type of vehicle,” and “it suggests that China is placing a high priority on the development of this weapon and that it is making progress.” Three Republican members of the U.S. Senate Committee on Armed Services expressed concern about China’s flight tests, declaring in a high-profile statement that China is clearly ahead of the U.S. in the field of hypersonic flight.

In 2015, in the list of winners and their achievements at the 3rd Fengru Aviation Science and Technology Elite Award published on the website of the Chinese Society of Aeronautics and Astronautics, the successful development of China’s scramjet engines and the completion of the autonomous flight tests of the hypersonic vehicles were introduced, and China became the second country after the U.S. to enable the autonomous flight of hypersonic vehicles powered by scramjet engines.

In May 2008, the Center for Hypersonic Science and Technology of CAS was established by eight related research institutes of CAS and the University of Science and Technology of China, with five research departments, including engine thrust performance, active cooling and structure, materials, aerodynamic configuration, and comprehensive ground experiments. It aims to contribute to the frontier development of hypersonic disciplines and major innovations in fundamental, strategic, and forward-looking issues of hypersonic flight through interdisciplinary and complementary research teams and platforms. Since 2008, the Chinese Society of Theoretical and Applied Mechanics, the Center for Hypersonic Science and Technology of CAS, and the Institute of Mechanics of CAS have jointly hosted the National Conference on Hypersonic Science and Technology, which has been held for eight years, mainly to present the latest research results in hypersonic fields such as hypersonic flow, hypersonic combustion, thermal protection, and comprehensive research in China.

In 2007, the NSFC launched the Plan in a timely manner, concerning key scientific issues related to hypersonic long-range maneuverable vehicles in near space. This is the first systematic basic hypersonic research plan in China, which focuses on four key scientific issues: aerodynamics in a near-space flight environment; advanced propulsion theories and methods; ultralight materials/structures, thermal environment prediction and thermal protection; and intelligent autonomous control theories and methods for hypersonic vehicles. The Plan aims to provide a fundamental understanding of physical phenomena related to near-space hypersonic flight; provide theories, methods, and means for key technological breakthroughs; develop innovative theories and methods for key basic scientific problems of near-space vehicles; enhance China's independent innovation capability in related fields; support the leapfrog development of related technologies; and last but not least, assemble and develop a wealth of excellent talent with theoretical and source technology innovation capabilities.

(i) In the field of aerodynamics in a near-space flight environment, we reached a new understanding of the characteristics of near-space hypersonic flow, proposed new theories of complex flow, revealed new mechanisms of complex flow, and improved the ability of physical and theoretical modeling. We have developed new methods and models for calculating complex flow, improved the ability of simulating complex flow, acquired a number of innovative hypersonic wind tunnel testing methods and means, and greatly improved the ability of ground simulation testing in China. A number of innovative hypersonic wind tunnel test methods and tools have been developed, which have greatly improved the capability and level of ground simulation tests in China. New methods of aerodynamic layout optimization were explored, and new methods of leading edge heat reduction, drag reduction, and flight control were proposed.

(ii) In the field of advanced propulsion theories and methods, the design methods of hypersonic inlets and special-shaped flow paths were innovated, which laid an important foundation for the coupled and efficient design of engine inlet and exhaust systems and combustors. The ignition, propagation, and flame stabilization mechanisms in the process of hypersonic combustion were deeply understood, and effective control methods were developed. New simulation methods were developed to improve the integration of propulsion systems and aircraft aerodynamic layouts. The development of the detonation theory in supersonic flow points the direction for the future design of detonation-based scramjet engines.

(iii) In the field of ultralight materials/structures, thermal environment prediction and thermal protection, we further revealed the response mechanism and thermal failure mechanism of UHT thermal protection materials and significantly improved the environmental resistance and toughness of UHTCs. We systematically developed the theory and analysis methods of lightweight multifunctional materials and structures and made important breakthroughs in the design and control methods of new microstructures, such as nano, porous, and lattice structures. We developed innovative methods and means for testing, characterization, and equivalent simulation of key material properties. We actively explored new materials, principles, and methods for non-ablative thermal protection and achieved breakthroughs in the research of thermal management composites, with performance reaching an internationally advanced level.

(iv) In the field of intelligent autonomous control theories and methods for hypersonic vehicles, the concept of fine attitude control for hypersonic waverider vehicles was proposed, and a new method for designing fine attitude control systems was developed. The concept of multichannel coordinated control for near-space hypersonic vehicles was proposed, and a new method for designing multichannel coordinated control systems for vehicles was developed. A new method of dynamics modeling of near-space hypersonic vehicles based on the model migration theory was proposed. The mechanism of attitude–aerodynamic force coupling of hypersonic vehicles was investigated, and coupling modeling and coordinated control design methods were proposed. The nonlinear coupled dynamics model of hypersonic vehicles was established, and the aerothermoelastic flutter control method was proposed.

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Major Research Achievements

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Members of the Steering Committee and invited experts selected 21 representative findings of the Plan, covering key scientific issues in four major research directions, including aerodynamics, propulsion, materials and structures, and control. These achievements fully reflect the research level of the Plan and its outstanding contribution to the overall targets.

1 Research on Transition and Turbulence in Hypersonic Flows

In hypersonic flight, the temperature in the boundary layer often exceeds 600 K. At this time, the vibrational degrees of freedom of molecules are excited, as a result of which the complete gas model is no longer applicable, and the influence of real gas effects caused by high temperature around the vehicle surface needs to be studied. At this point, the specific heat capacity of the gas is no longer constant but temperature-dependent, and the prediction of the laminar–turbulent transition becomes more complicated. On this basis, we investigated the flow stability, transition prediction, and transition mechanism of hypersonic flat-plate compressible boundary layers when the specific heat was temperature-dependent, and performed comparative calculations with the constant specific heat case. This was an experimental work in the field of aerodynamics in a near-space flight environment, and the following conclusions of this project were drawn.

(i) A parabolized stability equation (PSE) is proposed to predict the transition in subsonic and supersonic boundary layers, which accurately reproduces the mechanism of the breakdown process resulting from laminar–turbulent transition; that is, the correction of the mean flow profile leads to a significant change in its stability characteristics. The predicted transition of the flat-plate compressible boundary layer is consistent with the DNS results. The feasibility of PSE analysis of secondary instability in the *Ma* 4.5 supersonic boundary layer

S. Du (ed.), *Key Basic Scientific Problems on Near-Space Vehicles*, Reports of China's Basic Research, https://doi.org/10.1007/978-981-19-8907-0_3

is also verified, and the secondary instability mechanism is at work regardless of whether the 2D fundamental perturbation is a first-mode or second-mode Tollmien–Schlichting (T–S) wave. As the spanwise wavenumber of the 3D waves β varies, the amplification σ will reach a maximum; the amplification of 3D subharmonic waves varies with their spanwise wavenumber and 2D fundamental amplitude in a similar relationship to that obtained in incompressible boundary layers. However, even if the amplitude of the 2D waves reaches 2%, the maximum amplification of the 3D subharmonic waves is still much smaller than that of the most unstable second-mode 2D T–S waves, which further indicates that secondary instability is not the main mechanism leading to the supersonic boundary layer transition.

Based on this, a new method (PSE + DNS) was proposed to calculate the compressible boundary layer transition and turbulence, which is particularly suitable for transition and turbulence starting from small perturbations. In the laminar phase, PSE is used until breakdown occurs in the transition, and then DNS is used to calculate the transition process and turbulence, with the entrance condition being the perturbation obtained by the PSE method at that point. For both the subsonic and supersonic boundary layers, the transition and turbulence results are consistent with those obtained by DNS for the whole process. However, the new method has the advantage of requiring much less computational work than the DNS method.

(ii) To address the problem that the conventional e^N method cannot be applied to transition prediction in 3D flow fields, a simple algorithm was proposed based on the saddle-point method. Since the direction of the group velocity of the most unstable wave is generally close to the direction of the potential flow, the assumption that the amplitude growth rate is zero in the direction perpendicular to the potential flow can be used to perform the calculation, thereby omitting the iterative calculation in determining the disturbance wave parameters. The effect of flight altitude and angle of attack on the transition position is analyzed by predicting the transition of the boundary layer of circumferential flow of a composite body constituting a flat plate, a cone, and a cylinder by studying the distribution of N at Ma 10, altitudes of 30–45 km, and angles of attack of 0° and 10°, respectively. Whether there is a transition in the boundary layer of the vehicle is closely related to the flight altitude. For a typical shape with a high lift-to-drag ratio, not all parts of the vehicle will experience a natural transition at Ma 10. For example, it is impossible for the cylindrical part of the model to experience a natural transition. For those parts with transition, the transition area moves down or diminishes as the altitude increases, and eventually the natural transition will disappear from the model. Different angles of attack have different effects on different positions. An angle of attack of 10°, compared to 0°, increases the likelihood of transition in the windward flat plate and increases the transition area. For the cone on the leeward part, an angle of attack of 10° decreases the likelihood of transition, decreases the transition area, sometimes even to zero, and changes the transition position. In addition, to address the problem that the conventional e^N method cannot predict the transition of hypersonic pointed cones or blunt cones at small angles of attack at *Ma* 6, an improved e^N method was proposed, which takes into account not only the growth but also the decay of the perturbation, and the linear theory calculates the growth of the perturbation from the initial magnitude to 1% (considered as the transition position). The results showed that the new transition prediction was highly satisfactory. When using this method for the calculation of basic flows, the boundary layer equations can be used for small angles of attack with much less computational effort than DNS, and a very reasonable result can be obtained. However, the method relies on the correct prediction of the initial perturbation, which obviously depends on the accumulation and analysis of more flight data. Although these studies provide a theoretical basis for the rationality of the method, a large amount of experimental verification is needed.

(iii) A simple DNS method concerning the high-temperature real gas effect (variable specific heat) was proposed. By replacing the constant specific heat ratio with the equivalent specific heat ratio, DNS can be performed with the original equation for the constant specific heat and the flux splitting form (with few changes in the procedure). The results showed that the fundamental flow obtained by this method was consistent with that obtained by the direct splitting of the Navier–Stokes (N–S) equations in the case of variable specific heat. In addition, the effect of high-temperature real gas effects (variable specific heat) on the predicted transition was also investigated. The hypersonic boundary layers of the wedge and the zero-angle-of-attack blunt cone were investigated separately. The transition determined by both modal waves in the sharp wedge boundary layer is approximately 10 m from the leading edge, while the transition determined by both modal waves in the flat plate boundary layer is approximately 20 m from the leading edge, and the sharp wedge is closer to the leading edge than the flat plate as the incoming Mach number increases. Through numerical verification, it is found that the mean specific heat ratio is very close to the specific heat ratio calculated by the mean temperature. This provides a theoretical basis for calculating the turbulent flow in the variable specific heat gas model with only the mean temperature as the variable in the turbulent flow model. On this basis, the shear-stress transport (SST) turbulence model is used to verify the feasibility of using the turbulence model to calculate the turbulent flow of gases with variable specific heat.

(iv) The perturbation equations for the hypersonic flow with variable specific heat were developed to calculate the perturbation evolution and study the transitional mechanism. The perturbation equations are solved in two ways: either by developing similarity solutions using the Blasius equation or by obtaining the constant flow using DNS. Variable and constant values were used as specific heat values, and the results were compared with those obtained by DNS. In the calculations, the gas parameters at 40 km altitude were used at *Ma* 6. A 2D second-mode and a pair of 3D first-mode T–S waves were introduced at the inlet. The perturbation evolution was calculated with a variable specific heat and compared with the case of a constant specific heat and a flat boundary layer. The results showed that the perturbation evolution calculated using two different basic flows based on the perturbation equations was consistent with the results obtained via DNS. In the analysis of the effect of the high-temperature real gas effect (variable specific heat) on the predicted transition, the perturbation amplitude increased faster when the specific heat was variable than when it was constant, indicating that the transition should be closer to the leading edge, which is consistent with the prediction of the e^N method. Therefore, it is not feasible to choose a suitable equivalent specific heat capacity value as an approximate replacement for the case where the specific heat capacity is a function of temperature. For hypersonic vehicles, the temperature dependence of the specific heat capacity must be taken into account for the stability analysis of the boundary layer and the transition prediction.

(v) Studies on the aerodynamic heating of hypersonic flows were carried out. Based on the similarity of solutions for laminar boundary layer flows of hypersonic flat plates with variable specific heat under isothermal wall conditions, heat flux values were calculated for different incoming Mach numbers and wall temperatures and used as a calibration standard to compare the convective heat transfer coefficients of flat plate aerodynamic heating using the Eckert reference enthalpy technique. The results showed that, unlike incompressible fluids, the formula for the convective heat transfer coefficient (or Nusselt criterion) for hypersonic flow not only takes into account the effect of compressibility but also includes the wall temperature as a parameter. For wall temperatures of 0.1–0.9 times the adiabatic wall temperature at *Ma* 1–10, the maximum relative deviation between the two results was 2%. The formula of the Eckert reference enthalpy technique for the convective heat transfer coefficient has some generality and correctness in engineering practice, which provides a basis for further obtaining the accurate heat flux and thus for the design of thermal protection.

2 Research on Aerodynamic Principles and Structural Mechanics of Morphing Aircraft

With the increasing demand for flight efficiency, maneuverability, and multimission adaptability of aircraft, studies on intelligent morphing aircraft have gradually become a hot trend in the academia and aerospace industries in recent years. However, this is still a new research field, and the studies in various countries are still at different levels in their initial stages, and there is no clear and unified understanding of many concepts and key issues. It is generally believed that the intelligent morphing aircraft is a general term for the newly emerged concepts of aircraft designs, such as active aeroelastic wing, adaptive aerodynamic structure wing, intelligent wing, intelligent rotor, and variant aircraft, which are bionic designs mimicking the flying of birds, combining aerodynamics, aeroelastic mechanics, flight mechanics, intelligent materials and structures, modern mechanical engineering, modern control, information technology, multidisciplinary optimization, and bionics. The intelligent morphing aircraft is a multifunctional and high-performance vehicle concept that changes its geometric structure and aerodynamic shape to meet the requirements of various flight conditions and missions, thereby achieving full-range optimal performance.

The research on intelligent morphing aircraft is full of creativity, involving many academic frontiers and hotspots, such as unsteady aerodynamics, time-varying structural mechanics, aeroservoelasticity, mechanics of intelligent materials and structures, nonlinear system dynamics, intelligent perception, and control sciences. Among them, the design of lightweight and compact structures that can meet the aerodynamic load-bearing requirements and the morphing needs of the aircraft, which is the material basis for the realization of an intelligent morphing aircraft, has been a key element in the research on intelligent morphing aircraft, as well as an application bottleneck. The work in this project will contribute to the research on morphing aircraft in China. The main conclusions are listed as follows.

(i) The research team developed an aerodynamic layout of the subsonic, transonic, and hypersonic morphing aircraft for a wide range of velocities. The subsonic oblique wings and variable-sweep wings, transonic retractable wings and variable forward-sweep wings, hypersonic morphing osculating-cone waveriders, and oblique shock waverider configurations were studied from three aspects: aerodynamic layout design, circumferential flow calculation and experiment, and aerodynamic characteristics analysis. The effective morphing aerodynamic layout and its aerodynamic characteristics in near space were identified for a wide range of velocities. Analysis of the circumferential flow field for the rotating and shear variable-sweep wing–body configuration was conducted for a wide range of velocities. Using the numerical simulation method of viscous compressible flow and the trigonal-tetrahedron unstructured/structured hybrid grid, it was concluded that the shear variable-sweep wing has advantages over the rotating variable-sweep wing. The former has an obvious superior lift-to-drag ratio and resistance, mainly owing to the significant difference in the flow field structure caused by different variable-sweep approaches. Based on the calculation results of the aerodynamic characteristics of the two structures, a large shear variable-sweep approach for the outer wing section with relatively better aerodynamic characteristics was designed, and an experimental model based on the controllable morphing structure and continuous morphing pattern was developed. In the wind tunnel tests, the quasi-steady aerodynamic characteristic curve showed a large aerodynamic benefit of variable-sweep wings, while the unsteady aerodynamic characteristic curve showed a hysteresis loop, which may be due to the additional velocity effect of the wing and the hysteresis effect of the flow field structure. Wind tunnel tests of a variable-sweep and variable-span wing–body configuration showed that for a given angle of attack, if the value is within a certain range, then the lift, drag, and lift-to-drag ratio all decrease with the increasing sweepback angle and increase with the increasing span; both the maximum lift and minimum drag increase with the increasing sweepback angle; the maximum lift-to-drag ratio decreases with the increasing sweepback angle; and the maximum lift, minimum drag, and maximum lift-to-drag ratio all increase with the span. For a given lift, if its value is not too small (e.g., the lift coefficient is greater than 0.50), then the total drag increases with the sweepback. If its value is within a certain range, there is a unique span to make the total drag reach the theoretical minimum; the parasitic drag increases with the span; and the induced drag decreases with the increasing span. Considering the whole range of values, the morphing wing–body configuration can achieve drag optimization by its deformation. This can actually provide a new idea for aircraft drag reduction. Large-scale morphing can significantly change the aerodynamic characteristics of the vehicle, such as lift, drag, and lift-to-drag ratio, and thus enable the morphing aircraft to adapt to a variety of environments and missions and perform better than traditional fixed-form aircraft over the full flight cycle.

The study of the aerodynamic characteristics of morphing aircraft provides a realistic and feasible approach for the aerodynamic study and design of near-space morphing aircraft over a wide range of velocities. Therefore, the skin has sufficient stiffness to maintain the aerodynamic shape of the wing, which reduces the energy requirement of the actuator and keeps the airfoil smooth, continuous, and seamless during the morphing process, thus achieving excellent aerodynamic performance.

(ii) The phenomena and mechanisms of the unsteady aerodynamic characteristics during the typical morphing process were revealed. Analytical aerodynamic models for 2D and 3D airfoils were developed and studied through both theoretical analysis and wind tunnel tests. A numerical simulation scheme of the 2D airfoil (Joukowsky airfoil) morphing under low-speed, subsonic, and supersonic flow conditions was developed to study the unsteady aerodynamic characteristics of the morphing airfoil. When the normal motion velocity of airfoil deformation was much smaller than the incoming flow velocity of the incompressible ideal fluid, the effect of shedding or wake on the lift coefficients and the circumferential circulation of airfoil was very small, and the error of the quasi-steady calculation method of the morphing airfoil's lift coefficient was mainly due to the additional lift caused by the unsteady motion of the fluid. This unsteady additional lift coefficient was only relevant to the current flight attitude as well as the airfoil shape and deformation rate but irrelevant to the specific deformation history. The lift coefficient of the morphing airfoil was approximately equal to the quasi-steady calculation result superimposed on the corresponding unsteady additional lift coefficient. When the normal motion velocity of airfoil deformation was much less than the incoming flow velocity, the simple approximate correspondence between the quasi-steady lift coefficient and the unsteady additional lift coefficient of the morphing airfoil in two states, compressible and incompressible, was established, and the relationship between the unsteady lift coefficient and the incoming Mach number was identified. A simple correction method for the quasi-steady flow design was proposed for the 2D supersonic flow conditions, and the variation in the aerodynamic lift during the reciprocal deformation of the airfoil at different Mach numbers was analyzed and compared with that in the subsonic flow conditions.

The dynamic hysteresis of the variable-sweep-induced aerodynamic characteristics of the morphing aircraft and the influencing factors of the size and direction of the hysteresis loop were revealed. Based on the wind tunnel test results and some important concepts in mechanics, three physical effects were proposed, namely, the flow field hysteresis effect, additional motion effect, and solid wall implication effect. On this basis, the formation mechanism of unsteady aerodynamic characteristics in the variable-sweep process of morphing aircraft was demonstrated in both qualitative and quantitative ways, which can be used to model the aerodynamic characteristics for subsequent processes of the same type. It was found that the unsteady aerodynamic characteristic curves form hysteresis loops around the corresponding quasi-steady curves of the variable-sweep-wing unmanned aerial vehicle (UAV); the higher the UAV sweepback velocity is, the more significant the hysteresis effect; the UAV sweepback velocity of approximately 7.5°/s will cause the unsteady aerodynamic characteristic values to deviate from the corresponding quasi-steady values by more than 5%. The main reasons for the unsteady aerodynamic characteristics of the variable-sweep-wing UAV are the structural hysteresis of the flow field and the additional velocity of the wing. The above research provides a basis for studies of the transient aerodynamic characteristics of near-space morphing aircraft.

(iii) The mechanical and thermal properties of two types of intelligent morphing materials (shape memory polymers and SMA) were studied. SMA wires or particle-reinforced intelligent composites have special mechanical properties, and intelligent materials can be used as the main regulatory elements of adaptive structures owing to their mechanical properties and shape memory effects, which are different from those of traditional functional materials, their abilities to sense environmental conditions (e.g., temperature and stress) and actuate systems. SMA wires or particles can be embedded into the matrix of resin, metal, and composites, and designed by the principle of meso-mechanics to produce intelligent composites with distributed sensors and actuators for active control of the mechanical behavior of materials. Based on an in-depth study of the quasi-static thermal coupling properties and the intrinsic model of intelligent materials, the confined-state thermal coupling properties, incomplete phase transformation thermal coupling properties and strain-rate-dependent dynamic thermal coupling properties of two intelligent SMA materials were investigated. A "temperature memory" effect was discovered in the experimental measurement of the SMA partial reverse martensitic transformation, and the temperature at which the transformation was restarted was always approximately 3 K lower than the temperature at which the last thermal cycle was interrupted. The strain rate correlation was measured at low to medium strain rate tensile conditions, the stress yield plateau disappeared at quasi-static tensile conditions, and the slope of the stress–strain curve in the plastic section was positively correlated with the strain rate. Intelligent composites can also be considered an adaptive structure, which provides a material science basis for the design of morphing skins and structures.

(iv) The stable morphing structure and high-efficiency driving mechanism of the morphing aircraft were studied. The SMA actuator has the advantages of a compact structure, bidirectional output, high load-bearing capacity, high output force, high thrust-to-weight ratio and long stroke. Actuators designed and manufactured with SMA wire drive elements can achieve a large thrust and long stroke. The deformation of the flexible structure with the tension of the SMA wire has a great influence on the angular output of the actuator. Hence, the shape of such structure was characterized by a cubic B-spline curve; the deformation was analyzed using the finite element method; and the shape of such structure and the position of the SMA wire were optimized using genetic algorithms. The practical example showed that the optimization method could quickly and effectively obtain the shape of the flexible structure and the position of the SMA filament action point that maximizes the output angle of the SMA flexible torsion drive. Based on this, the concept of an "SMA intelligent material-motor hybrid actuator" combining the advantages of SMA actuators and motors was proposed with system dynamics modeling and analysis of the parallel mode and hybrid mode, and the first SMA-motor hybrid linear actuator prototype was developed. To address the problem of low resistance of the thicker wire actuator and the difficulty of electric heating, a new composite electric heating drive technology of winding enameled wire and simultaneous electric heating was invented, and a simplified thermodynamic model was built. This part of the research work provides a new technical approach for the efficient actuation and control of the intelligent morphing structure of aircraft and provides a dynamical basis for the design of morphing skins and structures.

3 Research on Multiple Approaches to Determining the Boundary Layer Separation on the Surface in Supersonic Flows

Hypersonic flow around a 3D projection on the surface of an object can lead to shock wave–boundary-layer interactions in the local flow field. Usually, the characteristics of the shock wave system and boundary layer in the flow field with interactions would change significantly compared to the situation without interactions, which leads to changes in the local pressure and heat flux on the object surface. These changes directly affect the structural design and aerodynamic characteristics of the aircraft. Simultaneously, the lateral jetting technology has a wide range of applications, and similar problems are encountered in vehicle attitude control, engine thrust vector control, and fuel injection and mixing in the combustor of ramjet engines. When a supersonic jet is injected laterally into a supersonic or hypersonic main stream, it will produce complex interactions between the shock wave systems and between the shock wave and boundary layer. To describe the formation and development of the flow field's characteristics and structures, this project aims to study the characteristics of supersonic incoming flow and supersonic jet and to point out the problems worthy of attention based on the current situation through three aspects: theoretical modeling, numerical methods, and simulation techniques; ground test simulation; and flight test verification. The study of hypersonic complex flow separation characteristics is a frontier research field in aerodynamics, which is extensive, comprehensive, and difficult. This study further elucidates the unsteady physical processes of complex flow separation at hypersonic velocities and promotes basic research on flow separation and its applications, thus providing comprehensive experimental techniques and quantitative and regular data that can be applied in various techniques. The experimental study of typical models (blunt fin/plate models with varied sweepback angles) and different test methods were used to reveal the steady and unsteady characteristics of hypersonic flow separation and to describe the spatial structure of flow separation by combining numerical simulations. The main conclusions of this project are as follows.

(i) The experimental study of laminar, transition, and turbulent flow separation was completed in the FD-20 hypersonic wind tunnel of the China Academy of Aerospace Aerodynamics (CAAA), including laminar and transition experiments at *Ma* 8 and turbulent experiments at *Ma* 6. The plate model was used to study flow attachment, the combined model with a blunt fin mounted on a plate was used to study flow separation, and the aerodynamic heating rate distribution was measured to further analyze the separation flow field characteristics. The boundary layer state and detailed heat flux distribution pattern of the attached flow on the flat plate model were identified, and the properties of the laminar and turbulent boundary layers were identified by a new type of sensor, which provides Reynolds number effects. Since changing the incoming flow parameters may affect the experimental results, the heat-flux sensor signal can be used to identify the transition zone and the transition Reynolds number and to indicate the location of the initial transition. Findings related to hypersonic laminar flow in past domestic and international studies are rather scarce, while for current and future near-space vehicles, long-range flight under hypersonic laminar, transition, and turbulence conditions is worth investigating. Therefore, this research has both novel scientific significance and important application prospects.

(ii) A variety of technical approaches were used to comprehensively reveal the characteristics of hypersonic flow separation. The three experimental techniques comprehensively used include measurement of surface heat flux distribution, pulsation pressure distribution, and high-speed schlieren imaging (2000 frames/s). The study of pulsation pressure variations in the separation zone revealed that wings with a 45° sweepback angle caused boundary layer separation; the laminar boundary layer was less resistant than the turbulent boundary layer; and laminar boundary layer separation occurred earlier and was more widespread. Similar flows can be observed between several measurement points outside the laminar separation zone. However, there is a significant difference between the flows inside and outside the separation zone. The pulsation pressure level in the laminar boundary layer is smaller than that in the turbulent boundary layer. Even so, the peak pulsation pressure is still very high in the laminar boundary layer. Therefore, the structural effects of pulsation pressure loading (including damage and early fatigue) owing to laminar boundary layer separation should not be ignored.

(iii) A complete set of steady and unsteady experimental data (including heat flux, pulsation pressure, and high-speed schlieren) on the separation flow characteristics at hypersonic velocities was provided, and the results cover not only the flow mechanism but also the mechanical/thermal load characteristics, which can provide both validation data for CFD and a reference for engineering design.

(iv) The development of a fine measurement element to measure the surface heat flux was completed. A highly integrated platinum-film heat-flux sensor was developed with dense measurement points and high precision, which can help capture peak and valley loads more accurately. Furthermore, the sensor performance is stable (after 23 high- and low-pressure eroding cycles, the damage rate is only 4%), making it a leading technology in China.

The laminar separation and flow characteristics study, the experimental techniques (high-speed schlieren test and high-Mach-number pulsation pressure measurement) and the numerical methods developed in this study have already been applied to the research on flow separation characteristics of near-space vehicles, flow field characteristics inside and outside the nozzle of the attitude control engine, and flow separation effects of various combinations of interceptor missiles. China's future focuses on the development of near-space hypersonic vehicles and aerospace vehicles that will face complex flow separation problems caused by pneumatic actuators, jet control, etc., and the accurate simulation of the separation phenomenon is still an important challenge for CFD. Especially in recent years, the upsurge in the development of hypersonic aircraft has been set off all over the world, and complicated phenomena such as shear-layer instability, pressure pulsation, shock oscillation, and vortex interaction have made the problem of hypersonic flow separation increasingly complicated, while the influence of flow separation on the aerodynamic characteristics of aircraft has become inevitable and increasingly more important. At present, research on flow separation is mainly based on simple shapes and standard models, and research on complex shapes and engineering calculation results is rare. There are many studies on the effects of flow separation on flow field characteristics such as pressure and heat flux distribution, while the effects of flight altitude, wall temperature, and angle of attack on flow separation are less studied. Therefore, the research findings of this project can strongly support the key technology research and engineering development of such aircraft.

4 Prediction of Aerodynamic Heating Characteristics and Exploration of High Heat Flux Control of Pointed Bodies in Low and Medium Near Space

Rarefied gas dynamics and high-temperature gas dynamics are two branches of fluid mechanics that are not very mature. The related flow problems include multiscale coupling of molecular collision, chemical reaction, and macroscopic flow, as well as multidisciplinary coupling of flow, heat transfer, and chemical reaction. The related theoretical analysis is very difficult. When solving engineering problems in the rarefied flow transition zone and chemical nonequilibrium flow, numerical simulations and empirical fitting formulas formed decades ago are heavily relied on, and almost no new theories have emerged in recent decades. Near-space hypersonic cruise vehicles, which have received wide attention in recent years, tend to employ leading edge shapes with pointed and thin wings and non-ablative thermal protection to pursue a high lift-to-drag ratio and excellent maneuverability. According to the Fay–Riddell equation, the stagnation heat flux of the leading edge is inversely proportional to the square root of its radius of curvature, and when the leading edge radius of curvature decreases and approaches zero, the stagnation heat flux will approach infinity, at which point the aerothermal protection will encounter new challenges. The problem of hypersonic thin transition zones, chemical nonequilibrium flow, and aerodynamic heating involves multiscale and multi-physical–chemical factors, and no mature theory is available to date. This project focused on the prediction of aerodynamic heating characteristics and exploration of high heat flux control of pointed bodies in low and medium near space, revealed the physical mechanism of hypersonic flow, proposed quantitative and physically meaningful flow criteria, and developed an aerothermal prediction bridge function suitable for rapid engineering estimation based on these criteria, thus building a theoretical engineering framework system for this problem. The main conclusions of this project are as follows.

(i) A physical model of the slightly blunt-headed stagnation point region in near-continuous flow was proposed to analyze the macroproperties of the rarefied gas effect, i.e., the progressive role of nonlinear factors in the flow and heat transfer. The ratio of nonlinear non-Fourier to linear Fourier heat flux is defined as the characteristic flow parameter W_r, and W_r measures the intensity of the rarefied gas effect over the entire flow regime. Therefore, for aerothermal problems, a non-Fourier heat transfer model was proposed, and a physically meaningful rarefied flow criterion W_r was introduced. The study showed that the criterion can simultaneously describe the evolution of aerothermal properties and the flow field structure of hypersonic rarefied flows and can explain the related physical mechanisms. Based on the physical meaning of W_r and subsequent extensions, a bridge function for predicting the stagnation point heat flux in hypersonic rarefied flows was developed to predict the aerodynamic heating of a pointed-nose cone owing to the rarefied gas effect. Through various comparisons, calculations and experimental measurements that support the DSMC method, the rationality of the theoretical analysis and the reliability of the bridge function were verified. In addition, the application of rarefaction standards in engineering practice was also discussed.

(ii) Based on the improved Lighthill–Freeman IDG (ideal dissociating gas) model and molecular dynamics theory, the dissociation and complex rate equation was established, and the mathematical expression of the chemical nonequilibrium flow model was proposed for the strong normal shock wave situation. Through physical analysis and approximate mathematical processing, a clear analytical relationship between the equilibrium dissociation degree after a strong shock, the nonequilibrium characteristic scale and the wavefront freestream was constructed, and a concise normalized formula describing the nonequilibrium transient process was developed. Based on these results, an explicit analytical relationship between the postshock chemical nonequilibrium flow characteristics and the wavefront freestream parameters was established, which can be used to directly predict the postshock nonequilibrium flow parameters by the wavefront freestream parameters. The DSMC results verified the theoretical modeling analysis and showed that the corresponding conclusions were reasonable and reliable in a wide range of practice, which enriches the theoretical framework of the nonequilibrium shock-dominated flow model and helps to evaluate the experimental data of hypersonic wind tunnels and analyze the CFD results.

(iii) Via the phenomenological analysis of flow characteristics, a generalized model of energy transfer and transformation along the stagnation point line was proposed, based on which the stagnation points can be divided into dissociation-dominant nonequilibrium flow outside the boundary layer and compound-dominant nonequilibrium flow inside the boundary layer. According to the shock wave mapping analysis, the nonequilibrium flow criterion Da_{d} (Damköhler number with physical significance) was introduced to predict the actual nonequilibrium flow state outside the boundary layer by the normalization equation. The study showed that the atomic compound effect in the boundary layer was equivalent to the change in the nonequilibrium dissociation degree outside the boundary layer, and the composite nonequilibrium criterion Da_{r} (specific Damköhler number) was derived. Based on Da_{d} and Da_{r}, a bridge function for the prediction of stagnation point heat flux in hypersonic chemical nonequilibrium flow was developed to characterize the effect of nonequilibrium chemical reactions on the boundary layer heat transfer. This bridge function is directly used for rapid engineering estimation of the aerodynamic heating of the aircraft.

(iv) The mechanism of the coupling effect between the rarefied gas effect and the nonequilibrium real gas effect was revealed, and the similarity pattern of the real gas flow under such a coupling effect was discussed. The new heat transfer characteristics of the pointed-nose cone in the medium-density nonequilibrium flow were emphasized, and the characteristics of the aerothermodynamic environment of the sharp leading edge of the next-generation vehicle were revealed. In addition, the aerothermal prediction model of the traditional large blunt-head reentry vehicle is not applicable to the next-generation vehicle.

This project was based on theoretical analysis of the model, combined with numerical calculations and verification of wind tunnel experimental data, and finally, the engineering theory was established. This is a viable alternative to the current heavy dependence on numerical simulations and empirical formulas in this field, which is rarely seen in China and abroad. The work has contributed to a deeper understanding of the microphysical mechanisms and macroregulations of rarefied gas and chemical nonequilibrium flows, supplemented and improved the theoretical systems of related disciplines, and has been successfully applied in engineering practice. It is of great significance to pursue disciplinary development for both rarefied gas dynamics and high-temperature real gas dynamics. More importantly, the engineering theories established in this study can provide theoretical and analytical support for engineering model testing. Research in this field relies heavily on numerical calculations and empirical fitting formulas, and wind tunnel and flight tests are very costly. For new problems encountered by near-space cruise vehicles, however, the reliability and robustness of these methods are questionable owing to the lack of a clear understanding of the flow mechanism. The results showed that there is no similarity pattern for the aerodynamic heating problem on the coupling of rarefied and nonequilibrium real gas effects, thus requiring the reproduction of real flow conditions and the use of full-size models in engineering experiments and calculations, which is difficult to achieve. Therefore, the difficulties encountered in experiments and calculations in turn highlight the importance and necessity of theoretical analysis.

5 Theoretical and Numerical Simulation Studies of 3D Compressible Unsteady Separation

Separation and vortices are common flow phenomena, and the vortices generated by 3D separation may increase the lift (e.g., vortex suction generated by streamwise vortices) and decrease the aerodynamic performance (e.g., vortex axis lift and vortex rupture) owing to the change in the separating flow regime. Therefore, it is of great practical importance to accurately predict separation and to conduct theoretical research on the occurrence and development of separation. The results of the separation theory can be used directly in the examination and analysis of the calculation results. The boundary conditions used in the current numerical calculations are not strictly theoretical near the separation point, and there are errors in the numerical values, which often result in large discrepancies between the calculated separation and the experiment, thus affecting the accurate calculation of the aerodynamic characteristics. To carry out the numerical analysis of 3D unsteady separation theory, it is necessary to solve problems such as 3D unsteady separation conditions (including fixed and moving walls) and separation flow patterns and verification. Therefore, it is necessary to study the unsteady separation criteria, 3D unsteady fixed-wall separation topology, multiscale numerical simulation methods, and complex unsteady separated flow mechanism. In addition, confrontation in the air is becoming increasingly fierce, and the requirements for aircraft maneuverability and agility are soaring: new aerospace vehicles are required to conduct large-range hypersonic maneuvering flight in near space. Not only does the flight angle of attack change over a wide range but also other motion parameters, such as the attitude angle, angular velocity, and angular acceleration, all change drastically with time, and there are obvious nonlinear coupling phenomena of aerodynamics, motion, structure, dynamics, and control. New aerospace vehicles should be strongly coupled, unsteady, nonlinear, and difficult to control. With the development of computer science and CFD, it is possible to carry out numerical virtual flight simulations with multidisciplinary coupling of aerodynamics, motion, and control, focusing on unsteady numerical simulations. Numerical virtual flight simulations need to be coupled with dynamic mesh generation, unsteady flow field calculation, solution of flight mechanics equations, and flight control pattern; if needed, structural elastic deformation and dynamic systems will also be considered. Numerical virtual flight can help the vehicle designer analyze and evaluate the nonlinear flight mechanics, stability, and control performance of the aircraft at the beginning and throughout the design process. In response to the current situation and demand, the main conclusions of this project are as follows.

(i) The theory of unsteady separated flow is established, and the difference between the compressible 3D unsteady separation pattern and the steady flow is clarified by the theory of unsteady separation pattern. With an incoming flow at *Ma* 1.8, the flow separation pattern consists of closed head separation and open cone separation. The cone separation will further generate multiple separations as the angle of attack increases, and the head of the blunt cone will start to have a complex combination of saddles and nodes. Although the topological structure of these singularities is complex, they conform to the distribution of singularities on the separation line. With an incoming flow at *Ma* 10.6, there is only the open separation mode when calculating the angle of attack. On this basis, the vector fields ξ and $\boldsymbol{n} \cdot \partial^2 \boldsymbol{V}/\partial n^2$, which do not depend on specific coordinates, were constructed, and the equivalent expression of the criterion was developed. This expression can be directly calculated using numerical simulation results, which is more conducive to numerical analysis.

(ii) The calculation results were presented for a series of 3D unsteady fixed-wall separation topologies, including lid-driven square cavity flow, unsteady flow around a blunt cone, and flow around an ellipsoid. In terms of the mechanism of complex unsteady separated flow, a new flow separation pattern starting from the limit cycle was discovered, and a new concept of a flow surface with a closed limit was proposed. A new type of cross-flow vortex with double delta wings was discovered, and high-accuracy numerical simulation results of the vortex substructure were obtained. A series of mechanisms of complex unsteady flow separation and vortex motion were revealed.

(iii) Numerical methods with high-order precision and high resolution were developed to meet the computational needs of complex multiscale unsteady flow. The windward or weighted essentially non-oscillatory (WENO) scheme was used instead of the Roe scheme in the characteristic decomposition process, which can completely eliminate the nonphysical fluctuations downstream of the shock wave and solve the divergence problem of the high-order precision WENO scheme for steady flows containing shock waves. The fifth-order WENO scheme is an ideal tool for numerical studies of flows containing strong shock waves and complex flow characteristics. In particular, the parallel efficiency of the fifth-order WENO parallel program developed in this project exceeded 98% in numerical calculations. Based on this, DNS studies on the interaction between a shock wave and a single vortex, the interaction between a shock wave and a vortex pair, the interaction between a shock wave and a 3D longitudinal vortex, and compressible isotropic turbulence were carried out to reveal the shock wave dynamics, the mechanism of vortex deformation, vortex rupture, and the generation mechanism of acoustic waves in the interaction between shock waves and vortices, as well as the flow field structure and flow mechanism of complex multiscale flows such as turbulence. The high-order WENO scheme, with good resolution and stability, is an ideal numerical method to study the above-mentioned flows containing strong intermittence and complex flow field structures. It was found that the interactions between the shock waves and strong vortices have multilevel characteristics, i.e., the interaction between the shock wave and the initial vortex, the interaction between the reflected shock wave and the deformed vortex, and the interaction between the small shock wave and the deformed vortex. The acoustic waves generated in the interaction between the shock and vortex pairs contain two regions: the linear region and the nonlinear region. In the linear region, the acoustic waves generated by the interaction between the shock and vortex pairs are a linear superposition of the acoustic waves generated by the shock wave and each vortex individually, while in the nonlinear region, the acoustic waves are related to the interaction between the shock wave and coupled vortex pairs. During the interaction between the shock waves and the longitudinal vortices, a multihelix structure was found in the vortex rupture region. In the isotropic turbulent pulsation field with a high initial turbulent Mach number, the presence of widely reported "small shock waves" was also found, which is a distinctive structural feature of compressible turbulence as opposed to incompressible turbulence.

(iv) An integrated numerical simulation method and a corresponding software system for virtual flight considering the coupling of aerodynamics, motion, and control (but not the effect of structural aeroelasticity) were initially developed, while only the most simplified open-loop and closed-loop control systems were implemented. Using this integrated method, a preliminary numerical simulation of the attitude angle control and overload control process of a narrow-bar maneuverable missile around a fixed center of mass with a fixed Mach number was carried out, which consists of the missile body and three sets of air rudders. The attitude of the missile body was controlled by the swing of the tail rudder. The input command was to change the angle of attack of the missile from 0 to the preset angle within a given time and to hold this angle. The calculated Mach numbers were 0.6 and 0.8, respectively. Owing to the large pitch inertia of the missile, a "loose coupling" strategy was adopted. The calculated response times coincide with the preset values of the control pattern simulation, which indicates that the integrated technique is capable of numerical simulation of such a virtual flight process and that the results are reasonable and reliable. In addition, a computation scheme with tight coupling of N–S equations, kinetic equations, and control patterns was developed, and the scope of the coupling method was investigated theoretically and numerically. The problem of geometric conservation patterns with unstructured grids was discussed. This simulation technology can be directly applied to the numerical simulation of the poststall maneuvers of the new-generation fighter, new maneuverable missiles, and large-range fast maneuvers of near-space vehicles to verify the control pattern of the aircraft, truly realize the multidisciplinary integration of design, reduce the risk of flight tests, and accelerate the development process of new aircraft.

6 Experimental Research on Flame Stabilization Mechanism of Hydrocarbon-Fueled Supersonic Combustors

The flame stabilization of hydrocarbon-fueled supersonic combustion is a highly coupled process of flow and combustion. Through a combination of experiments, numerical simulations and optical measurements, this project clarified the flame stabilization mode and conditions, the key influencing factors of flame mode transition, and the flame stabilization limit and influencing factors. The research is conducive to the disciplinary integration of fluids, reaction dynamics, and advanced optics, and is conducive to the close integration of basic disciplines with practical applications. The main conclusions of this project are as follows.

(i) A high-frequency pulsed schlieren system was developed independently to freeze the flow field by shortening the exposure time, and the pulsed discharge energy of the pulsed spark light source in the short exposure time is much higher than the background radiation energy of the combustor, which effectively eliminates the influence of the background radiation of the combustor. A clear flow structure image of supercritical kerosene combustion and its evolution process at *Ma* 3.0 was developed. On this basis, the clear flow field and flame structure of hydrocarbon-fueled supersonic combustion in the same transient state were developed by combining planar laser-induced fluorescence, CH spontaneous radiation, high-speed photography, wall pressure measurement, laser schlieren, and numerical simulation. The dynamic flame propagation process of supersonic combustion was analyzed; the characteristics of the flow field and combustion zone in different steady flame modes were studied; and the three possible steady flame modes and conditions of hydrocarbon-fueled supersonic combustion were discovered. The formation and evolution of the aerodynamic throat near the fuel injection point was found to be one of the main reasons for the oscillation between the two flame stabilization modes: cavity stabilization and jet wake stabilization.

(ii) The blowout limit pattern of hydrocarbon-fueled supersonic combustion under the effect of the main parameters was identified systematically for the first time, and the blowout mechanism of fuel-lean and fuel-rich combustion of cavity-stabilized combustion in supersonic flow was theoretically analyzed. The shear-layer stabilized combustion mode and the assumption of a flame substrate in the shear layer greatly simplified the analysis of the mechanism of cavity flame stabilization near the blowout limit, and the maintenance of the flame substrate in the shear layer was used as the stability criterion, which enabled the effective equivalent ratio and the Damköhler number to be directly related to the blowout criterion. Under the extreme conditions of rich and lean blowouts, the possible blowout process was analyzed from the 3D characteristics of the flow field, thereby realizing the association of the blowout limit model with incoming flow conditions, injection parameters, and cavity configuration. For the mass transport process, the introduction of the lateral jet penetration and mixing model in the supersonic flow made the determination of the effective equivalence ratio in the model more reasonable, while the modeling of the cavity coiling process provided a calculation model of the product mass fraction in the reflux zone in the quasi-steady state, which improved the coarse estimation method of the existing models and appropriately selected the empirical constants in the model. The blowout limit boundary, basically consistent with the experimental data, was identified, which proved the reliability of the model to some extent. Based on the understanding of this pattern, a combustion organization strategy was proposed that took into account the thrust performance, flame stability, combustor unstart, and heat release distribution. A new type of staggered double-cavity combustor configuration was also proposed. The effect of injector spacing on static pressure distribution, specific thrust increment and wall temperature distribution, the effect of the second injection stage on flame stability, and the effect of fuel flow ratio of two-stage injection on static pressure distribution and specific thrust increment were analyzed. The experimental results showed that at small injection intervals, when the engine thrust increases, the possibility of combustor unstart increases, while the wall temperature uniformity decreases, and the performance of the balanced combustor can be achieved by an optimal interval or a certain optimal interval. Increasing the equivalent ratio of fuel injection from the second injection stage can greatly reduce the blowout limit of the first injection stage, increase the distance between the two injectors, and reduce the stability of the second injection stage.

(iii) A new method of local oxygen supplementation was proposed to extend combustion stability. Based on the experimental results and numerical simulations, the mechanism of the effect of oxygen addition on the structural characteristics of the local flow field in the cavity and its combustion stability was analyzed. The flame structure in the cavity showed different characteristics with different oxygen supplementation injection methods, and the appropriate amount of oxygen supplementation can make up for the lack of air mass exchange rate in the cavity, improve the concentration conditions, and increase the combustion intensity. The difference in combustion intensity in the initial cavity results in two different combustion patterns in the self-sustained combustion stage with local and global feedbacks. In the case of unilateral oxygen supplementation only, the unilateral cavity combustion established a global pressure response and created a congested airflow environment, which is necessary for local flame expansion into the mainstream and heterogeneous flame propagation. The local oxygen supplementation method greatly improves flame stability and has engineering applications. In addition, pulsed combustion over the limits of continuous stable combustion can generate pulsed thrust.

(iv) A numerical simulation platform for large eddy simulation (LES) and Reynolds-averaged Navier–Stokes (RANS) was first developed for hydrocarbon-fueled supersonic combustion. In this platform, the flow–combustion interaction problem is solved by using a partial stirring model, and the effect of the chemical reaction mechanism is fully considered by using a simplified mechanism (e.g., simplified mechanism for kerosene with 39 species and 153 steps of reaction). In the aspect of gas jet mixing, the Kelvin–Helmholtz (K–H) wave system and the fine nozzle structure of the underexpanded jet were resolved for the first time; the large-scale helical structure and characteristics were found; and the flow destabilization process and mechanism were interpreted.

7 Construction and Experimental Validation of Hydrocarbon-Fueled Supersonic Combustion Mechanism

The combustion of hydrocarbon fuels is a very complex physical, chemical, and mechanical process in which a large number of intermediates, such as OH, CH, C_2, and other small radicals, are generated. To control the chemical reaction process of fuel combustion, it is necessary to study the main intermediates of combustion, to understand the main reaction steps of combustion, to obtain the key reaction kinetics and thermodynamic parameters, to analyze the factors affecting the reaction, to construct the mechanism of hydrocarbon fuel cracking–combustion detailed reaction by applying the theory, to establish the automatic generation program as well as the mechanism simplification method. Based on this, the main conclusions of this project are as follows.

(i) The ReaxGen-Combustion program, which autogenerates the reaction mechanism of hydrocarbon fuel, was developed for the study of reactions involving molecules and free radicals of C_5 and those with a higher number of carbon atoms. The program assumed that the high-temperature combustion reactions of alkanes are mainly characterized by the chain reaction mechanism of free radicals and that there are a limited number of high-temperature combustion reaction types, which are thus programmable. For hydrocarbon species larger than C_4, the reaction center is minimally affected by the molecular size and the surrounding environment, and the reaction kinetic parameters are determined by the categorization of the reaction. Using this program, the detailed mechanism of high-temperature combustion of methylcyclohexane was analyzed, and the corresponding subroutine modules were constructed according to the types of high-temperature combustion reactions of 20 alkanes. The starting reactants of high-carbon hydrocarbons call the corresponding reaction equations, and the resulting products do likewise, resulting in a series of chain reactions and corresponding kinetic parameters. The file containing kinetic data of the high-temperature combustion reaction of high-carbon hydrocarbons was collected by combining the core mechanism. The generated file of high-temperature combustion of methylcyclohexane contains 2034 reactions, and the file with thermodynamic data contains 344 species. The kinetic simulation of high-temperature combustion of methylcyclohexane using the reflected shock wave tube model verified the reasonableness of the detailed combustion mechanism, and the results were similar to those of the Pitz mechanism. On this basis, the detailed mechanism of the combustion reaction was constructed by applying ReaxGen-Combustion to a single *n*-decane as a single-component replacement model for domestic aviation kerosene in view of the complexity of the composition of aviation fuel. The detailed reaction mechanism of *n*-decane generated by the program contains 388 species and 2226 chemical reactions. The results showed that the single-component *n*-decane combustion reaction mechanism model can simulate and predict the combustion characteristics of aviation fuel in China more accurately. ReaxGen-Combustion, the first self-developed set of automatic reaction mechanism generation programs for aviation fuel in China, has changed the status quo of China's combustion simulation, which has depended on downloads from foreign programs.

(ii) The simplification method of the detailed chemical reaction kinetic mechanism was adopted to study *n*-dodecane, a substitute component of typical aviation fuel, and the simplification of the *n*-dodecane high-temperature combustion chemical kinetic mechanism was carried out. Using the multistep directed relation graph (DRG) method and the reaction removal method based on calculating the importance index of computational singular perturbation (CSP), the detailed mechanism of *n*-dodecane combustion consisting of 1279 components and 5056 reactions was simplified, and a chemical kinetics framework mechanism of *n*-dodecane high-temperature combustion with 59 species and 222 reaction steps was constructed. A comparison of the simplification results of the multi-step DRG and single-step DRG showed that the two-step DRG method was more suitable than the single-step DRG method for the simplification of detailed mechanisms with a large number of components. The framework mechanism was further analyzed using the CSP method on a time scale, and the quasi-steady-state species were accurately identified according to the contribution of substances in the slow mode, based on which a global simplified mechanism with 49 components was constructed by the quasi-steady-state approximation (QSSA) method. The analysis showed that both the framework mechanism and the global simplified mechanism can reproduce the results of the detailed mechanism for ignition delay time, concentration variation of major species and flameout under a wide range of simulation conditions. In comparison with the detailed mechanism, the framework mechanism can be more easily used to analyze the important species and reactions involved in *n*-dodecane high-temperature combustion. On the basis of this simplified framework, the calculation methods for thermodynamic and kinetic parameters of combustion reactions were established; simplified mechanism software and databases were developed; and the first online platform for combustion data sharing and combustion mechanism construction was initially constructed in China.

(iii) The self-ignition characteristics of hydrocarbon fuels such as trimethylbenzene and RP-3 were investigated on a heated shock wave tube platform, and the ignition delay time of the gas-phase RP-3/air mixture was tested at different temperatures, pressures, and equivalence ratios. The negative temperature coefficient effect of the ignition delay of domestically produced RP-3 aviation fuel was measured for the first time at 750–850 K and 10 atm (standard atmosphere), and the negative temperature coefficient decreases slightly with decreasing ignition temperature, which is mainly caused by the difference in combustion reaction mechanisms at high and low temperatures. Based on a large-scale data test, the expressions of ignition delay were derived for different equivalence ratios and pressures. The overall activation energy decreases when the pressure increases at the same equivalence ratio, and the increase in pressure leads to a decrease in the measured ignition delay time. Based on the composition identification of RP-3, 88.7% *n*-decane and 11.3% 1,2,4-trimethylbenzene were proposed as substitutes for RP-3. The simulation results of the ignition delay of the substitution using the kinetic mechanism proposed by N. Peter coincide with the experimental results, indicating that the RP-3 substitution model is suitable for RP-3 combustion. This work provides a basic database for the development and validation of alternative kinetic models for RP-3 aviation fuel.

(iv) A new series of online measuring methods for high-temperature thermophysical properties of aviation fuels (including density, flow velocity, heat sink, viscosity, and heat transfer coefficient) were established, and the chemical heat sink was defined and measured scientifically for the first time. The accurate measurement of pyrolysis gas density solved the problem of experimental measurement for the flow velocity of pyrolysis gas in the cooling channel at 750 °C and above. These measuring methods for high-temperature thermophysical properties have laid a foundation for tackling the key technologies in the active cooling design for scramjet engines.

(v) The first engineering model of domestic aviation fuel combustion was developed independently, and the numerical simulation of the inlets of the scramjet engine with reaction–turbulence coupling was successfully completed. The innovative solution of double-pressure cracking for active cooling of scramjet engines was proposed, which overcame the shortcomings of the supercritical active cooling method popular at home and abroad, significantly improved the chemical heat sink, eliminated the bottleneck problem of fuel coking during high-pressure cracking, and made a breakthrough in active cooling technology.

8 Mechanisms and Applications of Detonation Propagation and Deflagration-to-Detonation Transition in Supersonic Flows

Detonation, a type of combustion with a high heat release rate, has attracted much attention in propulsion. As an important development direction of advanced hypersonic propulsion technology, it has broad application prospects in propulsion systems. Detonation couples a strong shock wave and a violent chemical reaction after the wave and propagates at supersonic speed. It has the thermodynamic characteristics of isovolumetric combustion and can rapidly release more mechanical energy. In the development of detonation-based power systems, the initiation of detonation has been a key issue. Reliable initiation is one of the core technologies in the study of detonation. Direct initiation can use a large ignition energy so that the detonation can be formed within a relatively short period of time and relatively short distance and is thus an ignition method more suitable for practical application. In addition to strong shock waves and detonation waves, direct initiation can also be achieved by a highly chemically active hot jet. This project addressed the issues related to hot jet initiation and the propagation of detonation in supersonic flows, elucidated the mechanism of hot jet initiation in supersonic flows and the influence of key factors, and initially verified the feasibility of a detonation-based scramjet engine, thus laying a solid foundation for the development of a new concept efficient hypersonic ramjet engine in the future. The main conclusions of this project are as follows.

(i) Fine numerical simulation and experimental research were systematically carried out on hot jet detonation initiation and propagation in supersonic premixed gas: the feasibility of hot jet direct initiation of supersonic premixed gas was verified; the hot jet initiation mechanism and propagation pattern of supersonic premixed gas was clearly elucidated; the control function of the hot jet on detonation under supersonic incoming flow conditions was discussed; and the propagation mode of detonation waves under supersonic incoming flow conditions was investigated through experimental observations. Owing to the Kelvin–Helmholtz (K–H) instability, the hot jet injection into the supersonic flow field induces the formation of a shear-layer interface that acts as a free boundary and leads to an increase in the pressure after the detonation waves, which in turn contributes to the formation of overdriven detonation. By controlling the injection of the hot jet, the formation of the shear-layer free boundary can be controlled to control the propagation in the detonation waves of supersonic combustible mixtures. When the shear-layer free boundary is formed by the injected hot jet, an overdriven detonation is formed in the flow field; conversely, when the shear-layer free boundary disappears by shutting down the hot jet, the overdriven detonation in the flow field decays to a Chapman–Jouguet (C–J) detonation. The experimental results showed that after successful ignition, two propagating modes of detonation waves in supersonic premixed gas were observed and can be classified as pure oblique shock-induced combustion and oblique shock-induced combustion/Mach stem-induced detonation. The transition between the two propagating modes can occur.

In terms of the conditions for detonation, several parameters were investigated using adaptive mesh refinement in the object-oriented C+ + (AMROC) program. For the Mach number and pressure of supersonic combustible mixtures, there exist certain ranges for successful initiation; for the other parameters, including the Mach number, pressure and diameter of the hot jet, and the channel height, there exists a critical value for successful initiation. In particular, there is a range of Mach numbers ($Ma_{\infty\min}$, $Ma_{\infty\max}$) of supersonic combustible mixtures for detonation initiation. When Ma_{∞} exceeds this range, the hot jet cannot initiate detonation, and the flow field remains stable with either a shock wave or a shock wave reflection caused by the hot jet.

(ii) The initiation and propagation characteristics and patterns of the hot jet in supersonic premixed gas with nonuniform velocities and components were obtained for the first time worldwide, and a new flow phenomenon under nonuniform conditions was discovered. A systematic study of supersonic combustible mixtures with nonuniform velocities was carried out by high-precision numerical simulations, and a detailed reaction model with nine components (H_2, H, O, O_2, OH, H_2O, HO_2, H_2O_2, Ar) and 34 basic reactions was used to analyze the characteristics of hot jet initiation under velocity inhomogeneity and the mode of self-sustained propagation of the detonation waves after successful initiation. The results showed that in supersonic combustible mixtures with nonuniform velocities, when the hot jet-induced bow-shaped shock wave reached the interface, the shock wave would generate a turning angle at the interface to achieve postwave pressure matching at the interface. The Mach reflection at the upper wall eventually led to the formation of a local Mach stem-induced detonation wave near the interface, which resulted in local detonation initiation in the flow field. The triple wave points below the Mach stem-induced detonation wave travel forward along the bow-shaped shock wave, and the continuous reflection collision between the lower wall and the triple wave points above has a significant effect on the successful initiation of the lower half of the flow field. The resulting dynamically stable "oblique shock-induced combustion/Mach stem-induced detonation" structure formed in the supersonic combustible mixtures with nonuniform velocities propagates with a uniform velocity as a whole, generating two parallel slip lines behind the curved shock wave at the interface dividing the upper and lower flow fields; and four distinct velocity layer structures are formed owing to velocity stratification and curved shock waves at the interface. In addition, the experiments confirmed that in supersonic incoming flow with nonuniform velocities, by using the velocity of the lower half of the flow field as a reference and changing the velocity of the upper half, detonation initiation and propagation will show different characteristics and patterns. It was found that the range of Mach numbers that can achieve initiation changes from [3.7248, 4.656] in the uniform flow field to [2.328, 5.1216] in the nonuniform flow field. This shows that the range of incoming Mach numbers for successful initiation in supersonic flow fields with nonuniform velocities increases to a certain extent, which makes the detonation more adaptable to successful initiation.

Subsequently, based on the average chemical activity of the components, the detonation initiation and propagation modes in supersonic combustible mixtures with nonuniform components were investigated to explore the feasibility of initiation and self-sustained propagation under nonuniform supersonic incoming flow conditions. When the chemical reactivity of the mixture is high, initiation can eventually be achieved, independent of the spatial distribution of the mixture in the flow field, and four stages of development in the "lateral expansion of detonation" propagation mode occur in the flow field, i.e., detonation initiation, detonation decay, detonation quenching, and detonation reinitiation. When the mixture's reactivity is average, the detonation in the flow field can be fully realized, and the detonation overdrive in the upper and lower halves of the flow field is different. After the shutdown of the hot jet, a microoverdrive and microunderdrive detonation is eventually formed in the flow field, and a new "dynamically balanced combined detonation" propagation mode emerges. When the chemical activity of the mixture is low, detonation initiation cannot be successful; in this case, only by using a hot jet with higher energy can initiation be achieved. The different spatial distributions of the mixture have a key influence on the formation and evolution of the detonation; changing the relative distribution of the mixture in a fixed height channel or directly changing the channel height to adjust the distribution range of the different components in the mixture will ultimately affect the detonation propagation mode in the flow field.

(iii) The effect of different combustor configurations on detonation initiation and propagation was identified, and a thrust performance test of the supersonic detonation engine was carried out to measure the effective thrust of the detonation model engine. The combustor configuration with a cavity can achieve combustion stabilization through its oscillation and feedback mechanism and is widely used as a flame stabilization device in scramjet engines. Therefore, high-precision numerical simulations were conducted to investigate the detonation initiation and propagation modes as well as the self-sustaining mechanism of supersonic combustible mixtures using a hot jet in cavity-embedded channels and expanding channels. The cavity-embedded configuration and its position relative to the hot jet and the influence of the expansion profile and expansion angle on detonation initiation and self-sustained propagation were identified. The pressure oscillations generated by the slow combustion inside the cavity can enhance the intensity of the bow-shaped shock wave induced by the hot jet, thus contributing to the formation of Mach reflections and the generation of local initiation points. The cavity also plays a role in the detonation propagation of supersonic combustible mixtures, as the pressure acoustic waves generated by the slow combustion inside the cavity can cross the subsonic channel and act on the upstream detonation wavefront after the hot jet is shut down, ultimately resulting in the formation of weakly overdriven detonation waves. For a specific fluid flowing through a shallow cavity, there is a minimum cavity width $L_{\min}$. When the cavity width is less than $L_{\min}$, the cavity can only generate some pressure oscillation waves, and cavity oscillation cannot occur; thus, there is only a relatively small effect on the detonation initiation and propagation of supersonic combustible mixtures. When the cavity width is greater than $L_{\min}$, cavity oscillation will occur, and there will be a greater effect on detonation initiation and propagation. For shallow cavities, changing the depth of the cavity will not have an additional effect on the detonation initiation and propagation of supersonic combustible mixtures, while for deep cavities, the resonance oscillation of the cavity itself can accelerate the detonation initiation and propagation of supersonic combustible mixtures, which is a significant effect.

The viscous diffusion effect in the N–S equations can suppress the generation of small-scale vortex structures but has little influence on the highly unstable shear-layer vortex structure arising from the K–H instability and the vortex structure owing to the Richtmyer–Meshkov (R–M) instability. In a critically stable detonation, the flow field inhomogeneity caused by the expansion fan of the expanding channel leads to the generation of unburned jets behind the shock wave. Owing to the diffusion effect of the coherent structure generated by the separated shear layer and the R–M instability, the unburned jet is able to mix with the burned products, which in turn promotes the consumption of the unburned jet, accelerates the chemical heat release, and ultimately leads to the periodic propagation of the detonation under continuous hot jet injection conditions. After shutting down the hot jet, a high degree of turbulence develops behind the detonation wavefront owing to the generation of multiple subtriple wave point structures and subsequent slip shear layers. In contrast to the well-known R–M instability, the large-scale vortex structure in the highly unstable shear layer dominates the generation of turbulence and the rapid turbulent mixing of the unburned jet with the burned products, which in turn promotes the consumption and chemical heat release of the unburned jet so that the detonation wavefront is able to maintain the same position of stationary propagation through the periodic generation and consumption of the unburned jet. A relatively large expansion angle induces the formation of a larger unburned jet, which forms a larger vortex structure through the K–H instability. The turbulence caused by the vortex structure enhances the mixing rate of the unburned reactants with the burned products behind the Mach stem, which further accelerates the consumption of the unburned reactants. Although the increased expansion angle leads to higher expansion rates, the detonation propagates faster and with greater overdrive in the expansion channel.

(iv) Based on the application of adaptive grid encryption methods to improve computational efficiency, an adaptive parallel computing platform for 3D block structures was developed based on the Tianhe-2 supercomputer system. The detailed reaction model was used to simulate 3D large-scale detonation by adaptive grid encryption, and a 3D large-scale parallel numerical simulation of the hot jet initiation of supersonic premixed gas was carried out to study the detonation initiation and propagation characteristics of supersonic combustible mixtures under real 3D conditions, to analyze and compare the connection and difference between 2D and 3D situations, and thus to establish a finer 3D detonation wave structure and its development and evolution process. After the collision and reflection of the hot jet-induced bow-shaped shock wave surface with the sidewall and the upper wall surface, a Mach wave surface was formed at the upper wall surface and was tightly coupled with the subsequent combustion zone. A comparison of the 2D and 3D detonation simulations showed that the sidewall effect in the 3D detonation is critical to the initiation of supersonic combustible mixtures because the sidewall can facilitate the collision and reflection of the triple wave lines during the detonation process, while in the 2D simulation under the same conditions, the detonation cannot be successfully achieved. Under certain conditions, there is a critical width between the front and rear sidewalls of the 3D channel for successful initiation. When the channel width is greater than the critical value, the bow-shaped shock wave surface cannot achieve effective reflection, resulting in initiation failure. After successful initiation, the hot jet continues to inject, and overdrive propagation can be achieved for both 2D and 3D detonations, each with a stable degree of overdrive. Although the overdrive of the 3D detonation is smaller than that of the corresponding 2D detonation, the 3D detonation wavefront structure exhibits greater volatility. The propagation of the transverse wavefront and the collision of the triple wave lines can be realized in multiple directions under 3D conditions, making the wavefront structure of the 3D detonation more irregular than that of the 2D detonation. After the hot jet is removed, both 2D and 3D detonations gradually decay to C–J detonation. Compared with the 2D C–J detonation, the characteristic parameters of the 3D C–J detonation are almost the same as those of the 2D structure, including the C–J velocity, transverse velocity, oscillation period, and cell size. This indicates that the instability of the 2D detonation is reflected in the 3D detonation. However, unlike the 2D detonation, the reflection of the slapping waves off the sidewall in the 3D detonation allows the formation of a suboscillation mode in addition to the primary oscillation. The unique presence of slapping waves in the 3D detonation suggests that the 3D detonation exhibits greater instability than the 2D detonation. Comparative quantitative pressure analyses of 2D and 3D detonations validated the conclusion that 3D detonation exhibits greater volatility.

9 Research on a New Concept Compression System for Hypersonic Airflow

In a hypersonic vehicle with an air-breathing propulsion system, the high-speed airflow is first compressed in the inlet by a predefined compression surface to provide the required flow and flow field to the downstream combustor. As the first step in the thermal cycle of the propulsion system, the compression of the inlet airflow is one of the key processes. The main function of the compression system is to decelerate and pressurize the hypersonic airflow. The most important task is to design a compression system that organizes the shock wave or compression wave to compress the airflow in a reasonable, clever, and efficient way. Previous studies have found that the curved shock wave compression system, which consists of a specially designed curved compression surface, a concave curved shock wave, and an isentropic compression field between the compression surface and the shock wave, is a good combination of these new design concepts. Based on this, a new inverse design method for supersonic/hypersonic inlets was innovatively proposed and developed in this project, i.e., to design the whole or part of the compression inlet considering the aerodynamic parameter requirements of the inlet exit section or a rational layout of the aerodynamic parameters of the compression surface. This inverse design that goes against the flow completely depends on the aerodynamic parameters required by the downstream combustor; the design of the compression wall and the entire compression flow field relies on the pressure increase pattern for a given compression surface, the deceleration pattern for a given compression surface, or the shape of a given curved shock wave. This project is an attempt to explore a new approach to designing efficient and low-resistance hypersonic inlets. The main conclusions are as follows.

(i) An inverse design method for supersonic/hypersonic inlets with specified exit Mach number distributions was developed. Starting from the supersonic flow field at the specified exit, using the characteristic of flow information transmitted along the Mach line of the rotational characteristic line method, the dominant flow field and single-, double-, or multi-channel concave curved shock waves in the reverse flow direction were constructed in blocks, thereby creatively proposing a reasonable matching of the dominant zones of the curved compression flow field and the exit flow field. The inverse design processes of supersonic inlets and hypersonic inlets with specified exit Mach number distributions were enabled. To test the correctness of the above inverse design method, a test model was designed for a single-curved shock wave, given a freestream Mach number of $Ma_0 = 6$ and a linear distribution of the exit centerline Mach number of 3–4; and viscous numerical simulations and wind tunnel tests were conducted at the design point ($Ma_0 = 6$) and the off-design point ($Ma_0 = 5$). The curved shock waves were highly visible in the schlieren images. The test results agree well with the predetermined target values and the viscous numerical simulation results, proving the correctness of the inverse design method.

To meet the requirements of the actual engine inlet layout on the aircraft, given a predetermined exit Mach number distribution, the 2D rotational characteristic line theory can be used to realize the hypersonic 2D inlet inverse design for double- and triple-curved shock waves with controlled Mach number distribution on the compressed surface. The calculation results showed that, at the design point, the two inverse design methods can both achieve the predetermined exit Mach number distribution without viscous conditions; while with viscous conditions, the Mach number distribution in the main flow of the inlet exit region matches well with the predetermined distribution, and the Mach number in the main stream of the exit region still maintains good homogeneity at the relay point. The above results showed that both inverse design methods are feasible. Under the design conditions, when the capturing height, viscous-free exit height, viscous-free total pressure recovery coefficient of the design, and flow parameters at the assembly point are the same, the double-curved shock wave inverse design method has a simple wave system, and the flow coefficient at the relay point is 10.2% higher than that of the triple-curved shock wave; the internal contraction of the triple-curved shock wave inverse design method with viscous conditions is 17% smaller than that of the former, and the total pressure recovery coefficient at the design point and the relay point is 2.9% and 2% higher than that of the former, respectively.

Subsequently, an experimental study was conducted on the inverse design of the double-curved shock wave to achieve homogeneous outflow. The results showed that the double-curved design has achieved three objectives: the exit flow field is essentially homogeneous; the exit flow direction is horizontal; and the total pressure loss is less than that of the single-curved design for the same amount of compression. It was also found that this curved shock wave compression has some "correction" effect for inhomogeneous supersonic incoming flow (e.g., incoming flow of the precursor surface layer of hypersonic vehicles). This part of the study was limited to the inverse design of 2D compression channels. To extend this design concept to 3D compression flow channels, a preliminary approach to the inverse design of 3D inlets for a given exit Mach number spatial distribution was developed by extending the inverse design method for the above 2D case to a 3D case using a 2D slice superposition technique. For example, the inverse design of the 3D compression channel was carried out for a given exit Mach number linearly distributed along the y- and z-directions, and the feasibility of this design approach was confirmed.

(ii) A method of inverse design for the whole curved shock wave compression system was established and developed according to the pressure rise pattern of a given compression surface. The surface compression system can produce a dispersed, nonconverging isentropic compressional wave system, under which the leading edge of the shock wave can form a curved shock wave. The airflow is mainly compressed under the joint effect of the curved shock wave and the isentropic compressional wave system between the wall and the curved shock wave. The wall pressure rise pattern determines the pressure rise pattern in the flow line of the curved compression system, and the pressure gradients D_2 and D_3 in the middle section of the pressure rise pattern have the most significant effect on the flow field performance among the main design parameters. An S-shaped pressure rise pattern was proposed to improve the pressure distribution on the wall of the conventional isentropic compression surface, in which the slope of the pressure gradient in the leading edge is larger, while the slope of the pressure gradient in the trailing edge decreases gradually and approaches zero to avoid a relatively large inverse pressure gradient at the trailing edge. This can effectively improve the wall pressure distribution on the conventional isentropic compression surface and redistribute the pressurization effect on the whole wall, mainly using the front of the compression surface for airflow compression.

A curved compression system with a wall S-shaped pressure rise pattern was designed for a 2D inlet with a controlled wall pressure rise pattern. The length of the outer compression surface can be effectively reduced by 12% and 10% compared to the conventional triple-wedge compression and wedge + isentropic compression inlets, respectively, by using a curved shock wave to compress the airflow. In the design state, the performance of the wall S-shaped pattern inlet is between that of the conventional wedge + isentropic compression inlet and that of the conventional triple-wedge compression inlet for homogeneous incoming flow, while in the off-design state, the shape of the curved shock wave is insensitive to the Mach number variation of the incoming flow and causes less loss to the airflow, so the performance of the wall S-shaped pattern inlet is particularly advantageous. In particular, the flow coefficient reached 0.758 at the *Ma* 4 relay state, which was 9.5% and 7.5% higher than the conventional triple-wedge compression and wedge + isentropic compression inlets, respectively; and the total pressure recovery coefficient of the throat was 3.2% and 1.4% higher, respectively. For inhomogeneous incoming flow, the flow coefficients and total throat pressure recovery coefficients of all three inlets decrease as δ/H_C (H_C being the inlet capturing height) increases over the entire operating range. In the design state, the total throat pressure recovery coefficients of the three air inlets decrease by the same amount, while the flow coefficient and throat flow field distortion index of the air inlet with the wall S-shaped pressure rise pattern decrease the least. In the off-design state, the flow coefficient and total throat pressure recovery coefficient of the air inlet with a wall S-shaped pressure rise pattern decrease the least. In addition, the wall S-shaped pressure rise pattern of the air inlet had a certain correction effect on the inhomogeneous incoming flow. Since there are various forms of wall pressure rise patterns, this project investigated an S-shaped pressure rise pattern to effectively improve the wall pressure distribution at the isentropic compression surface and applied the resulting curved compression system to the design of a 2D air inlet. The performance of the inlet with curved shock wave compression was significantly better than that of the inlet with conventional compression.

After the side plate was improved with the curved compression system, the airflow was compressed mainly by isentropic compression supplemented by shock wave compression. Meanwhile, the overflow window of the lip was slightly reduced, with the largest reduction of 2.3% at *Ma* 5. Compared with the basic side inlet, the side inlet with curved compression had a slightly improved flow capture capability over the entire operating range, while its total throat pressure recovery coefficient was improved to a certain extent. The coefficient of recovery of the total throat pressure increased by 1.3% for the relay state at *Ma* 4 and by 2.4% for the design state at *Ma* 6. Therefore, the application of the curved compression system to the 3D side inlet reduced the lip spill window and changed the shock wave compression in the inlet to isentropic compression of the curved surface and weaker leading-edge shock wave compression. This improved the overall performance of the inlet, especially in the off-design conditions. On this basis, the application of the method to the design of multiple compression surfaces and air inlets, such as axisymmetric and internal contraction, was also investigated.

(iii) The inverse design method of the compression surface for a given compression surface deceleration pattern was developed. Because of the nonlinear correlation between the pressure rise pattern and the deceleration pattern of the compression surface and the difference between the two in the sensitivity of the compression efficiency, the inverse design method of the curved compression surface with a given deceleration pattern was developed. The curved compression system can produce an isentropic compression wave system with adjustable sparsity and not converging at one point; the shock wave on the leading edge forms a curved shock wave under the effect of this wave system. The curved shock wave and the isentropic compression between it and the wall surface jointly achieve the deceleration and pressurization of the airflow. Based on the design of a surface compression system with a given wall deceleration pattern, two conventional deceleration patterns with linear and quadratic wall Mach number distributions were studied. The influence of the main design parameters on the flow field performance was analyzed, and a design method with two sections of continuously distributed Mach number deceleration patterns was developed. The flow field performance of the curved compression system with a linear wall Mach number deceleration pattern is most affected by the slope A of the linear Mach number variation, while the flow field performance of the curved compression system with a quadratic wall Mach number deceleration pattern is directly affected by the leading edge compression angle δ_0 and the compression surface pressurization ratio π_d and is not sensitive to the variation of the slope C and the decreasing coefficient D of the deceleration rate $\mathrm{d}Ma(x)/\mathrm{d}x$. When the wall deceleration pattern is designed in two sections, the flow field performance is affected by the coupling of slopes A_1 and A_2 of the linear variation of the Mach number in the two compression wall sections and is not sensitive to the variation of the deflection angle δ_c on the first compression surface. However, the flow field performance of the curved compression system is mainly affected by the deflection angle δ_c of the first compression surface when a combination of quadratic and linear deceleration patterns is used. In terms of the distribution of the wall and exit parameters, the curved compression system of the wall Mach number quadratic deceleration pattern is very similar to the isentropic compression surface, as they both mainly use the back of the compression surface to decelerate and pressurize the airflow. The wall Mach number of the curved compression system with a linear deceleration pattern decreases at a uniform rate, making full use of the entire compression surface to decelerate the airflow, and thus the pressure gradient at the wall changes moderately, avoiding large pressure gradient changes at the end. When the wall adopts two sections of continuously distributed deceleration patterns, the flow characteristics of the compression surface are close to those of the curved compression system with linear and quadratic deceleration patterns, except that it is easier to control the change in the compression degree along the flow direction when the deceleration pattern is designed in two sections so that the parameter distribution at the end of the wall tends to change more gently.

The 2D hypersonic curved shock wave inlet was designed with curved compression systems of different deceleration patterns as the outer compression surface of the inlet and was compared with the conventional 2D inlet with triple-wedge compression and the 2D inlet with S-shaped wall pressure rise patterns under the same constraint conditions. The results showed that the outer compression surface of the inlet with a linear wall deceleration pattern was able to form curved shock waves; the length of the outer compression surface was shortened by 7% compared with that of the conventional triple-wedge compression inlet with the same constraints; and the wall pressure rise pattern was also significantly improved. For homogeneous incoming flow, the performance of the inlet with a linear wall deceleration pattern was better in the operating range of *Ma* 4–6. In particular, the flow coefficient reached 0.783 at *Ma* 4, which was 13.2% higher than that of a conventional triple-wedge compression hypersonic 2D inlet, and the total pressure recovery coefficient of the throat was also improved by 4.5%. For inhomogeneous incoming flow, a large amount of precursor flow does not significantly affect the outer compression section of this inlet and has less impact on the wall pressure rise pattern and performance. Compared with the inlet with an S-shaped pressure rise pattern, the inlet with a controlled wall deceleration pattern did not form a significant curved shock wave, so the lengths of their outer compression surface were relatively long. In particular, the length of the outer compression surface of the inlet increased by 29% when the wall adopted the quadratic deceleration pattern compared with that of the S-shaped pressure rise pattern. This resulted in a 7.2% increase in the flow coefficient for the S-shaped pressure rise pattern at *Ma* 4. In addition, the flow field on the outer compression surface of the inlet with a controlled wall deceleration pattern was closer to isentropic compression, resulting in relatively less flow loss to the airflow. The total pressure recovery coefficient of the throat was increased by more than 22% compared to the inlet with an S-shaped pressure rise pattern at *Ma* 6 under cruising conditions.

(iv) In contrast to the conventional wave distribution design, the aerodynamic design of a 2D surface compression hypersonic inlet with excellent performance can be achieved by combining a multiobjective optimization strategy with the pressure gradients at the characteristic points of the outer and inner compression surfaces. Based on this idea, this project developed an inverse design method for the whole 2D inlet by specifying the pressure distribution pattern, realized the integrated design of the inner and outer compression of the air inlet with controlled aerodynamic parameters, and established an inverse design method and an automated design optimization platform based on the software program i-Sight for the whole flow channel of the 2D surface compression inlet, which made the large-scale scheme calculation possible and enabled large-scale solution calculation and multiobjective automatic optimization of air inlet design through optimization algorithms. The preliminary study showed that the inlet design scheme with excellent overall performance can be developed from the completed sample calculation scheme, which has a total pressure recovery coefficient of 0.68 at *Ma* 6 and a flow coefficient of 0.77 at *Ma* 4. After increasing the sample points, reducing the design variable space, and using a new proxy model to improve the estimation precision of the approximate model, the algorithm can be directly used for further optimization. The wind tunnel experiments and numerical calculations showed that the designed inlet had excellent performance and that this inverse design method was feasible.

(v) A new design method for the basic flow field (BFF) of the internal contraction inlet was developed, and an inverse design method for the BFF with the inverse tangential pressure rise pattern was proposed. To make the airflow deceleration and pressure rise process more reasonable and to improve the compression efficiency, the design parameters were adjusted, and a new "4-wave 4-region" axisymmetric BFF was designed, which decomposed the stronger leading-edge incoming curved shock wave in the "2-wave 3-region" axisymmetric BFF with a controlled Mach number distribution into a weaker curved shock wave and a partially isentropic compression wave while diffusing the reflected shock wave into an isentropic compression wave, thus forming the structure of the "4-wave 4-region" in the BFF. The compression efficiency of this new "4-wave 4-region" BFF was significantly increased: the pressure rise ratio at the design point was increased by 9.8%; the total pressure recovery coefficient was increased by 8.6%; and the flow coefficient at the relay point was increased by 2.7%. Compared with the inlet designed by the "2-wave 3-region" BFF, the inlet designed by the "4-wave 4-region" BFF had less vortex at the exit, higher compression efficiency, and stronger flow capture capability. The flow coefficient of the relay point in the new inlet reached 0.876, which was increased by 5.7%, and the total pressure recovery coefficients at Ma_∞ 6 and 7 were 9.8% and 23.6% higher, respectively.

On this basis, a design method of an axisymmetric BFF with a controlled Mach number distribution for a given shock wave configuration was proposed, as well as a "2-wave 3-region" BFF and a double-curved "3-wave 4-region" BFF. This method has improved the controllability and aerodynamic performance of the BFF: on one hand, the inverse design of the total pressure recovery coefficient of the shock wave distribution with a given shock wave radial can control the compression efficiency of the BFF; on the other, the inverse design of the Mach number distribution of the compression surface can control the ratio of isentropic compression to shock wave compression, the stability of the surface layer, and the internal contraction ratio. The "2-wave 3-region" BFF maintains a relatively high compression efficiency, with a pressure rise ratio of 12.3 and a total pressure recovery factor of 0.962 at the design point. The "3-wave 4-region" BFF designed by Henderson's theory is also more efficient in compression, with a uniform and short exit, and the pressure rise ratio and total pressure recovery coefficient at the design point are 20.1 and 0.912, respectively. This new axisymmetric BFF of the double-curved "3-wave 4-region" opens up a new way of thinking for internal contraction inlets.

(vi) A new concept of an elastic curved compression surface with controllable deformation for a wide Mach-number range was proposed to control the flow coefficient of hypersonic inlets through the design approach of aerodynamic variable geometry. For the 2D inlet, the numerical calculation method was used to produce elastic deformation by changing the pressure difference between the upper and lower compression surfaces to control the flow coefficient of the inlet at different Mach numbers. The numerical calculation results showed that within the pressure range of 3000–20,000 Pa in the bottom pressure chamber, the flow coefficient ranges of the incoming flow at *Ma* 4.5, 5, 5.5, and 6.0 are 0.787–0.889, 0.856–0.972, 0.923–1.000, and 1.000, respectively. This shows that the design of the variable geometry of the elastic compression surface is feasible, and the goal of controlling the flow coefficient over a wide range of Mach numbers has been achieved. At the same Mach number, the higher the pressure in the pressure chamber is, the farther the curved shock wave is from the lip; at the same pressure in the chamber, the farther the working Mach number of the inlet is from the design point, the farther the curved shock wave is from the lip. Using the aerodynamic adjustment method of this project, it is possible to improve the flow coefficient of the basic inlet with fixed geometry at *Ma* 4.5, 5, 5.5, and 6.0 by 14.2%, 13.7%, 7.4%, and 0%, respectively, and to slightly improve the total pressure recovery coefficient at the exit. This indicates that the design of the variable geometry of the elastic compression surface can improve the inlet performance at the Mach number of the off-design point, which provides a new method to improve the inlet performance at the off-design point.

(vii) The experimental study of five typical types of curved compression hypersonic inlets was completed. Given the pressure rise and deceleration patterns of the compression surface, five typical inlet models with fully curved compression surfaces and curved shock waves (2D, axisymmetric, side pressure, inward turning, and osculating waverider) were designed. The wind tunnel tests were completed, and the resulting performance was identified, which confirmed the feasibility of the new design method.

10 Research on Actively Cooled Ceramic Matrix Composites and Structures Thereof

The scramjet engine is a key component of near-space hypersonic vehicles. It has a high combustion temperature, high pressure, long duration, and strict dimensional requirements, without ablation, which cannot be met by conventional materials. At high temperatures, actively cooled C/SiC materials have good thermal and mechanical properties and can meet non-ablative requirements and are thus the most promising thermal protection material for scramjet combustors. This project aims at the screening of C/SiC active cooling internal protection material systems, material modification, optimization of prefabricated body structures, connection methods and processes, and preparation and simulation of cooling structures, with the purpose of exploring the internal thermal protection problem of scramjet engines and promoting scramjet research and development in China. Simultaneously, the database of C/SiC composites was improved to enhance the designability, and the research results can be applied to the design of rocket engines and high-temperature gas engines. The main conclusions of this project are as follows.

(i) A C/SiC active cooling material system was developed. Through material modification, the service temperature of C/SiC can be increased by 350 °C; the prefabricated structure can be optimized to improve the applicability of C/SiC and provide the material system and constraints for the active cooling configuration design.

(ii) The material process system for C/SiC brazing was determined. The brazing of C/SiC to metal was studied to determine the structure and the role of the brazing layer. Research on brazing between C/SiC and C/SiC was continued, and innovative brazing material components were developed to form a brazing process system for application in C/SiC configuration fabrication.

(iii) Four C/SiC active cooling configurations were designed and manufactured. The C/SiC active cooling structures designed and manufactured in China for the first time include brazed, riveted, composite, and combined configurations.

(iv) Experimental verification and simulation studies were conducted for the above four configurations. The effect of the C/SiC active cooling configurations was verified experimentally to provide a reference for configuration optimization.

11 Research on Autonomous Coordinated Control of Near-Space Hypersonic Vehicles

Owing to the complex mechanical characteristics and load conditions of hypersonic vehicles, different types of motion coupling with different physical mechanisms will be generated. Thus, the coupling, decoupling conditions, and the utilization and coordination of coupling become important challenges for hypersonic vehicle control. The narrow flight corridor in near space and the rarefied air will inevitably lead to the reduction of rudder effectiveness, resulting in the need to use other actuators. To ensure maneuvering under such complex conditions, control problems such as dynamic allocation and coordination of heterogeneous actuators as well as redundant control inputs need to be solved. To address these issues, this project focused on the nature of multiple inputs, the allocation of heterogeneous actuators, the interaction suppression and allocation of the control system, etc. The following conclusions were drawn.

(i) For the multiactuator problem frequently encountered in modern aircraft, the nature of multiple inputs, especially the problem of redundant control in multi-input systems, was refined and solved, and the sufficient and necessary conditions for the strict degradation of the quadratic performance index owing to multiple redundant inputs were defined. In the case of nonstrict degradation of the quality index, eigenvectors of the Hamiltonian and generalized eigenvectors were used to determine the initial set of states. Similar results were given for the quality assurance of uncertain systems with multiple redundant inputs. A similar study of the H_2 optimal control problem based on state feedback and dynamic output feedback controllers was conducted, and a method based on linear matrix inequalities and the Riccati equation was developed. The role of multiple inputs in improving the optimal control was verified; an iterative optimization algorithm was proposed, i.e., the input matrix can be selected to make the quadratic performance index of the multi-input system fall faster; and a robust least-squares method for multi-input allocation was developed.

(ii) A multichannel coupled model for vehicle attitude control was developed, and the main characteristics of parameter variation under hypersonic conditions and the main sources of model uncertainty were analyzed. To address the interaction suppression and control allocation problems of flight control systems with an uncertain control effect matrix, an H_2/H_∞ feedback controller was designed to suppress the interaction noise while ensuring the stability of the closed-loop model, and a feedforward controller was used to track the reference signal and provide feedback of the three-axis torque controlling the flight attitude. In the case of uncertainty in the control validity matrix, robust least-squares were used to tackle the problem of allocating the three-axis torque to the corresponding control surfaces, keeping the control input within the required range. A comparison of robust least-squares control allocation (RLSCA) and pseudoinverse control allocation was made for the problem of RLSCA with nonstructural and structural uncertainties. Three RLSCA methods were proposed when the control efficiency matrix had unstructured, structured, and linear fractional structured uncertainties. Simulation results showed that using this method, the control effector was able to deflect smoothly and generate the desired virtual control torque. RLSCA was robust to the uncertainties in the control effect matrix.

(iii) For the effects of aerodynamic coupling, kinematic cross-coupling, and inertial cross-coupling, the decoupleability was analyzed, and robust, fault-tolerant, adaptive, and anti-saturation control methods were developed. The flight control was combined with the active flow control of the plasma actuators. For the practical situation of transient change of the plasma actuator aerodynamic control performance of the finite actuator state, the bang-bang control method of the plasma actuator was proposed. Wind tunnel tests have verified the effect of plasma flow control, showing that the flow control authority of plasma is limited. The flow control effect is only apparent at the pitch angle near the stall speed. However, flight control simulations showed that with the proposed optimal control method, even a small plasma-induced roll moment can perform the maneuvering task well and meet the flight quality requirements. In addition, the volatile plasma-induced roll moment interaction can be adequately suppressed. Therefore, the proposed bang-bang control method is a promising approach for the control design of plasma actuators. Current and future work includes airfoil flight control in a wind tunnel and final flight tests.

A new adaptive nonsingular terminal sliding-mode controller (ANTSMC) was proposed for a class of nonlinear systems with perturbations and uncertainties. According to Lyapunov stability theory, we proved that a switching controller that can avoid singularities by using terminal sliding surfaces can achieve finite-time convergence to reach the sliding phase. The adaptive approach was introduced into the controller design under the premise that the perturbations and uncertainties are bounded and the boundaries are unknown so that the proposed ANTSMC has better robustness. This method was applied to the design of integrated missile guidance control, and a partially integrated missile guidance control system with a dual-loop controller structure was designed based on the ANTSMC method for the inherent characteristics of the time-scale separation of the translational and rotational missile dynamics. The outer loop was constructed to directly generate the command for the pitch rate, and then the inner loop was designed to track the outer loop command. The simulation results of the nonlinear longitudinal missile model demonstrated the effectiveness of ANTSMC. Compared with the smooth second-order sliding-mode control method in the literature, ANTSMC was found to have better convergence. On this basis, a coordinated control method for coupled systems of hypersonic vehicles was proposed, which breaks the tradition of using decoupling control methods and provides a new approach for vehicle control applications.

(iv) The methods of robust decentralized control and controller switching jitter suppression were proposed to address the multi-model control problem arising from the full envelope flight of hypersonic vehicles. Based on the H_∞

control theory and the stability theory of system switching, a robust stabilizing controller design method was proposed for the multi-input multi-output (MIMO) multi-model switching system that can effectively suppress jitter and improve transient response performance. By introducing the idea of proportional-integral control, an extended state feedback controller was designed based on the model tracking method to transform the controller design problem into a linear matrix inequality that is easy to solve. This controller not only enables the controlled subsystems to meet the required performance specifications and suppress the large perturbation during the switching process but is also very robust and can adapt well to the changes in the object parameters. More importantly, the controller can guarantee the global stability of the multi-model switching system at the same time, and the simulation results verify the effectiveness of this method for the control of the system. On the basis of this method and the failures of U.S. hypersonic vehicles, the control difficulty of large-angle-of-attack flights was analyzed, and a more reasonable robust control method was proposed.

12 Research on Hypersonic Vehicle Modeling and Fine Attitude Control

The fine attitude control of hypersonic vehicles generally requires the dynamic error to be less than $\pm 1°$. However, the hypersonic vehicle is not a purely rigid body and generates elastic vibrations during flight. These inherent vibrations are measured by sensors and fed back to the rudder system through the control system, which affects the control precision of the flight control system and further influences the working quality of the scramjet engine and even the success of the flight. Therefore, to achieve fine attitude control of hypersonic vehicles, it is necessary to model the fine-grained elastic vibration of the vehicle, build a high-precision measurement and sensing system, and develop fine control algorithms and finely optimized control strategies. This project focused on the basic scientific problem of fast and high-precision attitude control in hypersonic flight and proposed the concept of "fine attitude control" for the first time in China.

(i) The concept of "fine attitude control" of hypersonic vehicles was proposed and gradually improved according to the special requirements of the flight attitude of air-breathing hypersonic vehicles, from simple attitude precision to attitude precision + attitude angular velocity suppression. The main basic scientific problems of cruise control in air-breathing hypersonic vehicles were identified.

(ii) An analytical description of the aerodynamic characteristics of hypersonic vehicles under different operating conditions of scramjet engines was established. The changes in the aerodynamic characteristics of the hypersonic vehicle were analyzed in three operating states: with the engine inlet closed, the engine inlet open (cold air state), and engine ignition. When the inlet is closed, the drag and pitching moment of the vehicle are relatively large; when the inlet is open, the drag, lift, and pitching moment are reduced. For the transverse motion, the lateral force, roll moment, and yaw moment are also reduced after the inlet is opened. The difference between the aerodynamic characteristics of the aircraft in the cold and ignition states of the engine is relatively small. The lifting-body configuration has longitudinal static stability in all three engine states but will decrease with the increasing angle of attack. In addition, the lateral static instability, directional static stability, and elevator angle have an effect on the lateral static stability. The angle of attack has an effect on the rudder effectiveness, which varies at different rudder declination angles. Based on the results of the research on the factors affecting the aerodynamic characteristics of the lifting body, the analytical expressions of the aerodynamic coefficients and moment coefficients were fitted. The fitted analytical results were generally consistent with the calculated results and can thus serve as a reference for the next step in the control system design. Based on this, a mathematical model of the hypersonic vehicle and its aerodynamic and structural parameters, including the near-space atmosphere, the scramjet engine, the electric engine, and the lifting-body configuration, was developed. This model is still being refined and will provide a public and comparable research object for the study of flight control methods for air-breathing hypersonic vehicles.

(iii) The problems of high dynamic pressure separation and fast adjustment of attitude perturbation in the separation section of hypersonic vehicles were studied using linear and nonlinear methods, and control methods that meet the requirements of ballistic timing and precision were proposed. In the interstage separation of hypersonic vehicles, the flight speed is approximately *Ma* 6, and the dynamic pressure is approximately 70 kPa, so there will be strong aerodynamic interference between the front and rear bodies, which will cause an attitude deviation of the vehicle. To suppress this aerodynamic interference, a preset rudder bias design method based on a cerebellar model articulation controller (CMAC) neural network was proposed. This method uses the nonlinear mapping effect of the CMAC neural network to improve its structure. Instead of using the network output as the input for the adaptive learning of the network, the method uses the angle of attack after separation and calculates the required preset rudder bias values for different separation interferences. It was verified in simulations where the above preset rudder bias design method can effectively suppress the effect of the separation aerodynamic interference on the angle of attack and sideslip angle, and reduce the angle deviation from 4° to 0.02°. The flight environment and characteristics in the cruising state of hypersonic vehicles were studied. The important conclusion was drawn that the flight control design in the cruising state can be linearized at the operating points and studied according to the linearization method.

(iv) The fine attitude control of hypersonic vehicles under the conditions of aeroelasticity and engine vibration was studied, and a method that met the requirements of fine attitude control was proposed. The influence of elastic vibration on the fine attitude control of hypersonic vehicles was analyzed by taking the longitudinal channel of a hypersonic vehicle as an example, and a control-oriented mathematical model of an elastic hypersonic vehicle was established. Considering the large-scale perturbation of aerodynamic parameters and modal parameters, an active control strategy was adopted, and a fine attitude control system was designed based on robust H_∞ control theory and linear quadratic regulator (LQR) theory. A large number of simulations showed that by taking into account the measurement noise, rudder nonlinearity, and wide range of parameter perturbation, the control system can track the rigid angle of attack well, suppress the elastic angle of attack, ensure the $\pm 0.4°$ precision of the local angle of attack at the inlet, and meet the requirements of fine attitude control of hypersonic vehicles. In addition, based on the idea of adaptive modal suppression, a fine attitude control system was designed to address the uncertainties of aerodynamic and structural modal parameters unique to hypersonic vehicles, including a robust H_∞ filter to observe the rigid body modal state information, an LQR rigid body controller to improve the tracking performance, a structural modal observer to identify the curved modal frequency in real time, and a structural filter. Simulations showed that the designed control system can well track the rigid angle of attack and suppress the elastic angle of attack with a random perturbation of $\pm 20\%$ of the aerodynamic parameters and $\pm 30\%$ of the modal frequency to keep the control precision of the angle of attack at the inlet of the scramjet engine within $\pm 0.6°$ and meet the requirements of fine attitude control. The above work focused on the basic scientific problem of fast and high-precision attitude control in hypersonic flight and strongly supported research on hypersonic vehicles in China.

13 Research on Attitude–Aerodynamic Coupling Mechanism and Coordinated Control of Near-Space Hypersonic Vehicles

In this project, the attitude–aerodynamic coupling mechanism, modeling characterization method, and control method were studied to draw the following conclusions.

(i) The attitude–aerodynamic coupling mechanism was analyzed. Based on the in-depth study of the near-space flight environment, the typical special flight modes of hypersonic vehicles, and the possible flight envelopes, the attitude–aerodynamic coupling of hypersonic vehicles was regarded as a coupling problem of states and parameters of complex fast-changing systems, and the specific characterization of the coupling and interaction was achieved.

(ii) The coupled attitude–aerodynamic modeling method was studied. Two coupling description methods and modeling approaches were proposed: (a) the mutual coupling between parameters and states in the dynamic equations is attributed to the additional coupling term added to the model, and the parameter variation term is stripped from the additional coupling term based on the strict parameter feedback theory; (b) the coupled state/parameter dimensional expansion description method was proposed on the premise of the approximation pattern of state-influenced parameters to develop the state/parameter dimensional expansion dynamical system by combining the expression of parameter variation with the system dynamic equation in a general nonlinear system. On the basis of the state/parameter dimensional expansion, the attitude–aerodynamic coupling characteristics of near-space hypersonic vehicles were analyzed. The coupling matrix expressions of the fast and slow loops of each channel of the near-space vehicle were developed based on the state/parameter dimensional expansion, and the coupling characteristics were analyzed by combining them with typical trajectories.

(iii) The following control methods were proposed based on the additional coupling term of the parameters. (a) An adaptive controller method based on the estimation of the invariant flow regime parameters, which can be applied to near-space hypersonic vehicle simulation. To address the problem that the invariant flow regime parameter estimation method requires one-to-one correspondence between the state quantity and the parameter coupling term, a parameter estimation method and an adaptive control pattern based on Lyapunov functions were proposed. The method is suitable for solving the longitudinal attitude control problem of near-space flight, which is no longer limited by the number of parameter coupling terms. For the dynamic model of air-breathing hypersonic vehicles with uncertain aerodynamic parameters, the adaptive backstepping controller was designed to compensate for the mismatch and uncertainty in the model to ensure that the vehicle tracks the desired changes in altitude, velocity, angle of attack, and pitch rate. A Lyapunov-based stability analysis was used to ensure the asymptotic stability of the controller state. The numerical simulation results based on MATLAB can prove the effectiveness of the controller designed in this project. (b) A dynamic inverse control method based on the fuzzy neural network observer, which can be used to solve the output tracking control problem in the case of severe coupling of states and parameters. The observer can well estimate the additional coupling term of the parameters, and the controller designed in combination with the dynamic inverse method eliminates the effect of state–parameter coupling on the system. To adapt to the case of nonfull-state output, a control method based on a fuzzy neural network observer was proposed to address the more general problem of decoupling control of MIMO systems. In particular, the RLV (reusable launch vehicle) dynamic inverse control method based on a B-spline fuzzy neural network disturbance observer was proposed for RLVs with large uncertainties in the reentry flight parameters and external disturbances. A nonlinear dynamic inverse controller was designed for the nominal system to ensure the control performance. The parameter uncertainty and external disturbance were considered as the total disturbance of the system, and the B-spline fuzzy neural network disturbance observer was designed to estimate and construct the compensating control signal into the system. The designed control method was simulated by introducing aerodynamic parameter deviation and disturbance torque and comparing it with the controller of the traditional dynamic inverse method. The results showed that the proposed RLV attitude control method is robust to parameter uncertainties and external disturbances and compensates for the lack of precise models required by the dynamic inverse method. (c) A decoupling control method based on the nonlinear extended state observer (NESO), which can be used to solve the attitude control problem of hypersonic vehicles. Based on the decentralized control, the coupled dynamics and uncertainties were reduced to generalized uncertainty terms, and then the NESO method was used to give estimates and add them to the decentralized control pattern as compensation signals. The theoretical derivation showed that this method can guarantee a consistent and bounded tracking error of the closed-loop system. Simulations on a hypersonic glider model and comparisons with the traditional split-channel feedback control method showed that this decoupling control method can provide superior control and eliminate the effects of channel coupling and uncertainty to a large extent.

(iv) The following control methods were proposed based on the state/parameter dimensional expansion. (a) An observer-based robust control method. By expanding the parameters into new system states, the dynamical equations after dimensional expansion were developed, the state–parameter coupling and the system disturbance terms were separated; the feedback control was established to eliminate the influence of the coupling; and the LMI satisfying H_∞ performance was developed for the system disturbance terms, which was used to determine the controller feedback gain and the observer gain. This method has already been successfully used to solve the attitude–aerodynamic coupling problem in the design of near-space vehicle attitude controllers. (b) A sliding-mode control method based on state/parameter dimensional expansion. The sliding-mode motion, which is unique to sliding-mode variable structure control, can effectively reduce the dependence on accurate mathematical models and ensure the performance of the observer in the presence of uncertain system parameters or external disturbance. The stability of the closed-loop system under the action of the sliding-mode observer and the sliding-mode control pattern was demonstrated using a sliding-mode control method based on Lyapunov stability theory. This method can be used to address the attitude control problem of near-space hypersonic vehicles. To address the RLV reentry attitude control problem, sliding-mode control was combined with the robust controller of nonlinear dynamic inverse technology. To improve the robustness of the nonlinear dynamic inverse controller, the sliding-mode term was introduced into the nonlinear dynamic inverse controller and designed for the high performance of the nominal system. To select the appropriate magnitude of the sliding-mode term to ensure the robustness of the system and avoid unnecessarily large jitter, a nonlinear estimator based on an NESO was developed to estimate the interaction between the nominal system and the nonlinear object. The magnitude of the sliding-mode term was adjusted online, and the stability of the whole system was analyzed using disturbance estimation. In addition, the feasibility and effectiveness of the controller were verified in an RLV simulation.

14 Theoretical and Experimental Research on Hypersonic Aeroservoelasticity, and Hypersonic Flutter Suppression and Experimental Research

The aeroservoelastic analysis and design of hypersonic vehicles is an important research direction in the field of aeroelasticity. This project has studied the key basic problems of hypersonic aeroelasticity in depth and provided new methods and ideas for the development of the aeroelasticity discipline from theoretical and experimental aspects. A new research area of aeroelasticity research was identified through intensive modeling and experimental research of the rudder system, which fully embodies the interdisciplinary characteristics of aeroelasticity and promotes the development of this discipline. The main conclusions of this project are as follows.

(i) A systematic and complete structural dynamics, aerodynamic and aeroservoelastic analysis method for hypersonic vehicles was identified, and a robust aeroservoelastic analysis method was developed. The method can take into account the structural mass, stiffness, rudder characteristics, control gain, and thermal environment perturbations of the hypersonic vehicle and is more practical for analyzing the structure.

(ii) The stability and response analysis method of the aeroelastic properties of the coupled rudder engine/surface system was proposed and developed, and a passive suppression method of rudder system flutter was developed. For the servo flutter problem caused by the coupling of structural, aerodynamic and flight control systems, an active control scheme based on the Hilbert–Huang transform with adaptive structural filtering was proposed, which took into account the in-flight characteristics of structural modal change. An active control pattern design method for hypersonic flutter suppression was identified, which can effectively improve the flutter boundary.

(iii) Ground simulation tests of 2D wing section flutter and aeroservoelasticity were proposed. To solve the problem of reduced loading of distributed aerodynamic forces in the simulation test, an aerodynamic simulation method was developed to represent the distributed unsteady aerodynamic forces by applying concentrated forces at a finite number of excitation points, and the time domain flutter analysis was performed for different configurations of airfoil models at subsonic and supersonic speeds. When the number of excitation points/pickup points is 4, the time domain flutter results can be controlled within 3% of the theoretical frequency domain flutter results, suggesting general agreement, which verifies the generality and feasibility of the modeling method. A method was proposed to find the unsteady aerodynamic reduction loading point by targeting the vibration pattern of the key flutter mode. Through the genetic optimization of the airfoil models of different configurations, the optimal position of the excitation points/pickup points for aerodynamic damping was found, and the flutter characteristics of aerodynamic damping in accordance with the theory can still be identified. The method can be used not only for aerodynamic reduction but also for other scenarios where there are specific requirements for the number and location of transducers/exciters, such as modal testing. The unsteady aerodynamic simulation method proposed in this project is highly effective and universal and can be used as a reliable theoretical basis for ground simulation tests of flutter. The key problem of coordinated control of multiple exciters was solved, and the ground semiphysical simulation test method of rudder system flutter and aeroservoelasticity was developed. The precision of the ground simulation test of the rudder system and the calculation precision of the theoretical model were verified by wind tunnel tests. The ground simulation test method of rudder system flutter is a new aeroelasticity test method for hypersonic vehicles that is high-precision, time-saving, and cost-saving.

15 Nonlinear Coupled Dynamics and Thermoelastic Flutter Control of Hypersonic Vehicles (Fostering Project), and Aerothermoelastic Panel Flutter in Hypersonic Flows and Active Control Thereof (Continuous Project)

Panel flutter is a self-excited vibration phenomenon caused by the coupling of inertial force, elastic force, and aerodynamic force triggered by the air flow over the surface of the panel when exposed to supersonic flow. Panel flutter will cause large lateral panel vibration, which may lead to fatigue failure of the vehicle structure. During flight, the increase in panel temperature owing to aerothermal effects will generate thermal stresses and moments in the panel, reducing the curved stiffness of the panel. In addition, the aerodynamic noise generated by the aircraft engine and supersonic flow can also harm the fatigue life of the panel. To reduce the damage of panel flutter to the vehicle structure, researchers usually use different active and passive control methods to increase the critical flutter dynamic pressure or reduce the vibration amplitude of the panel during flutter. In this project, the following conclusions were drawn from studies on the flutter pattern of wings or panels in hypersonic flows, the passive control method of panel flutter suppression, and the effect of a dynamic vibration absorber (DVA) on composite panel flutter suppression.

(i) The nonlinear aerodynamic flutter pattern and the critical flutter dynamic pressure of the panel in hypersonic flows were identified for the wings or panels in hypersonic flows. Based on Kirchhoff’s and von Karman’s large deformation theories, the nonlinear aerodynamic force on the surface of the panel was simulated by the third-order piston theory, and the nonlinear flutter model of the panel in hypersonic flows was established according to Hamilton’s principle. The first four orders of modal functions of the four-sided simply supported panel were constructed by the double sine function; the derived nonlinear partial differential equations (PDEs) were transformed into the system of ordinary differential equations (ODEs) by Galerkin discretizations; and finally, the reduced-order ODEs were simulated numerically by the Runge–Kutta methods. By analyzing the eigenvalues of the linear coefficient matrix of the ODEs, the critical flutter dynamic pressure of the panel was identified, and the superposition of panel flutter was explained from the perspective of nonlinear dynamics. The effect of aerodynamic damping on the critical flutter dynamic pressure and flutter frequency of the panel was revealed, and the aerodynamic damping can stabilize the system at the beginning of flutter. The difference between the dimensionless dynamic pressure (DDP) identified in the analysis for the real part of the eigenvalue and the DDP identified when the frequencies coincided was 2.7%. Aerodynamic damping also has a great influence on the amplitude of limit cycle oscillation and vibration frequency. After comparing the eigenvalues of matrix $\boldsymbol{A}$ with and without linear aerodynamic damping, we found that the DDP, when μ changes from negative to positive, is defined as the critical flutter dynamic pressure of the system, which is more reasonable than the DDP when superposition occurs.

For the flutter characteristics of the panel under combined acoustic and thermal excitation, the thermal strain was introduced into the geometric relationship of the panel, and the noise excitation of the panel surface was simulated by zero-mean Gaussian white noise with finite bandwidths. Hamilton's principle was used to develop the differential equation of motion for the panel under combined acoustic and thermal excitation. The effects of the laying angle, temperature, and sound pressure level decibel on the panel flutter were investigated, and the dynamic response of the panel under the combined acoustic and thermal effects was simulated numerically to identify the aerodynamic flutter pattern of the composite panel. The results showed that the critical flutter dynamic pressure of the panel decreases rapidly with the increasing laying angle; the increase in temperature decreases the critical flutter dynamic pressure of the panel and increases the amplitude of limit cycle flutter of the panel; the flutter characteristics of the panel will not change when the temperature increase does not reach the critical buckling temperature of the panel, but after the temperature increase exceeds the critical buckling temperature of the panel, the panel will show period-doubling motion and chaotic motion; when the temperature rises, the influence of noise excitation will gradually weaken, resulting in a smaller lateral vibration amplitude of the panel under combined acoustic and thermal excitation than that under noise excitation alone; when the sound pressure is relatively low, the lateral vibration characteristics of the panel are affected by temperature changes, while when the sound pressure is high, the random vibration of the panel caused by noise excitation must also be considered.

(ii) Two passive control methods of composite panel flutter suppression were proposed. For the panel with reinforcement installed on the leeward surface, a new passive method was developed to analyze the ribbed panel flutter. The traditional finite element method was abandoned. Based on two reasonable assumptions, the ribbed panel was equated to a panel subsystem and a rib subsystem, and the forces between the two subsystems were simplified to an action–reaction pair uniformly distributed along the *y*-direction. Then, the PDEs of motion for the panel subsystem and the rib subsystem were developed using Hamilton's principle and the Euler–Bernoulli beam theory, respectively. Based on the deformation coordination relationship, the modal function of the panel subsystem was substituted into the PDE of motion for the rib subsystem; the expression of the interacting forces between the two subsystems was derived and then substituted into the model of the panel subsystem; thus, the PDEs for the panel subsystem were developed. Then, the PDEs of motion for the panel subsystem were discretized into ODEs by Galerkin discretizations. Finally, based on Galerkin discretizations, a new method for analyzing the flutter of ribbed panels was developed. The Runge–Kutta methods were used for numerical simulation of the ODEs. The results showed that the reinforcing ribs parallel to the flow direction on the leeward side of the panel can increase the critical flutter dynamic pressure and reduce the amplitude of limit cycle flutter; when the additional mass is the same, the thicker ribs are better than the wider ribs in increasing the critical flutter velocity and reducing the amplitude of limit cycle flutter. The optimal rib-adding solution is to lay a rib as thick as the additional mass allows in the middle of the leeward side of the panel. Given limited space, the rib should be placed as close to the middle of the panel as possible.

With respect to the passive suppression method of the DVA, a flutter model of a composite panel with a DVA in supersonic flows was constructed. The effect of the DVA on the critical flutter dynamic pressure and the amplitude of limit cycle flutter of the panel was analyzed by installing the DVA on the leeward side of the panel. Considering the coupling of the DVA and the panel, the interacting forces between the DVA and the panel were described as a function of the relative displacement and relative velocity between the DVA and the panel; the differential equations of motion for the panel and the DVA were developed by using Hamilton's principle and Newton's second law, respectively; and the differential equations of motion for the coupled DVA–panel system were finally established in light of the interacting forces between them. The PDEs of motion were discretized by Galerkin discretizations, and the system was simulated numerically by fourth-order Runge–Kutta methods. Considering the DVA–panel interaction during model construction, changes in the DVA parameters will cause the inherent frequency of the coupled DVA–panel system, avoiding the phenomenon that the vibration suppression of the DVA only occurs at a single frequency. Numerical calculations showed that the introduction of the DVA can increase the critical flutter dynamic pressure of the panel over a wide range and reduce the amplitude of limit cycle flutter. By studying the effect of the DVA parameters on the panel flutter suppression, we found that the flutter suppression principle of the DVA is to increase the flutter superposition frequency of the system. When the selected DVA mass parameters cause the superposition of high-order frequencies of the panel, the DVA can simultaneously increase the critical flutter dynamic pressure and suppress the amplitude of limit cycle flutter; however, when the selected DVA mass parameters cause the superposition of low-order frequencies of the panel, the suppression of DVA may fail; the flutter suppression effect of the DVA decreases with the increasing stiffness coefficient and increases with the damping coefficient; when the DVA is installed near the middle of the panel, it can better suppress the amplitude of the panel flutter, while when the DVA is installed near the boundaries of the panel, chaos may occur in the panel. Changes in the DVA parameters will result in the flutter superposition frequency jumping between the lower- and higher-order intrinsic frequencies. The results of the optimal design for the DVA mounting position using the jump in the flutter superposition frequency showed that the critical flutter dynamic pressure of the panel is increased by 51.7% when the flutter frequency reaches the maximum, and a large suppression of the flutter amplitude is achieved over a wide range of DDP. Only when the DDP of the panel reaches nearly two times that of the critical flutter vibration will complex dynamics phenomena such as period-doubling bifurcation and chaos appear.

(iii) An active suppression method of composite panel flutter was developed using piezoelectric actuators and SMAs for active suppression. In the modeling process, the previously used finite element method was abandoned, and a 1D Brinson model was used to describe the restoring force generated by the SMA. The PDEs of motion for the SMA panel were developed by Hamilton's principle, and the ODEs of motion for the system were developed by Galerkin discretizations. A new method was developed to analyze the flutter of the SMA panel. The stability region and the thermal flutter boundary of the system were analyzed by nonlinear theories. The numerical analysis for the effects of parameters such as laying angle, laying position, number of parts, prestrain, and temperature of the SMA on the thermal buckling and flutter suppression of the panel indicates that the laying of SMA in the single ply of the composite laminate can improve the critical flutter dynamic pressure of the panel; the optimal laying angle of the SMA is along the direction of airflow; and the laying of SMA in the outer single ply has a greater effect on the flutter stability boundary of the composite panel. By heating the SMA while increasing its number of parts and prestrain, the critical flutter dynamic pressure and critical thermal buckling temperature of the panel can be increased, and both the amplitude of limit cycle flutter and thermal buckling deformation amplitude can be reduced.

With the active suppression method of piezoelectric actuators, the direct and inverse piezoelectric effects of piezoelectric materials were used as sensors and actuators for active vibration control of the panel, and the dynamic equations of a 3D microcurved panel with piezoelectric sheets and films on the leeward side were developed by using the stress function method, which took into account the thermal stress, preload, and geometric nonlinearity. Taking the panel under supersonic operating conditions as an example, the Bubnov–Galerkin method was used to obtain the ODE, and the LQR control law was proposed. The dynamic response of the 3D panel at different microcurved heights with and without control was compared, which verified the control effectiveness.

A composite control strategy combining LQR and cubic nonlinear feedback was designed to effectively improve the flutter instability velocity and nonlinear flutter instability boundary of the system and reduce the amplitude of limit cycle flutter after flutter instability. Based on the LQR active control strategy, a progressive LQR control strategy was proposed using different airflow velocities as reference values, which significantly increased the critical flutter velocity of the system at a small cost. The proposed composite control strategy and progressive LQR control strategy for panel flutter are also applicable to the increase in critical flutter velocity and flutter suppression of wings in subsonic flow, as well as the increase in critical velocity and suppression of serpentine motion of high-speed trains, which will be a great contribution to the related scientific research.

16 Mechanical Properties Testing and Failure Mechanisms of Thermal Protective Coatings in High-Temperature Environments

The acquisition of high-quality images/videos in high-temperature environments is a prerequisite for online visualization measurements, in which the object shape, deformation, and temperature are measured based on image processing methods. In high-temperature ground tests, there are factors that seriously affect image acquisition, such as high-temperature light radiation, airflow disturbance, air refractive index change, and aero–optical effect. Oxidation and ablation on the surface of objects at high temperatures will cause changes in surface morphology, in which case deformation measuring methods based on traditional point-marking methods or digital imaging techniques are no longer applicable. In addition, numerous high-temperature tests on thermal protection structures/materials have shown that the mechanical–chemical coupling is one of the most prominent features of high-temperature oxidation and failure, but there is a lack of coupled stress–diffusion models for high-temperature oxidation. The intrinsic mechanism of oxide film growth and its failure evolution depends on the morphology and stress measurement of the film/substrate structure, but the air refractive index change at high temperatures seriously affects the conventional laser interference-based film/substrate measuring method. To address the problems of online measurements and failure mechanisms in high-temperature environments, this project developed high-temperature optics and independent high-temperature experimental scientific instruments for structure-level visualization and measurement of ground tests of thermal protection systems. A test method and an online observation tool for oxidation–stress coupling of materials at micro- and nanoscales based on laser interference and a high-temperature nano indenter were developed, and a high-temperature coupled oxidation–stress–chemical model was established to explain the microscopic failure mechanism. The combination of macro- and micro-visualization measurement techniques enabled systematic characterization of materials and structures for performance testing and failure mechanism studies. The main conclusions of this project are as follows.

(i) High-temperature optics were developed, and high-temperature experimental scientific instruments were developed independently for the visualization and measurement of ground tests in thermal protection systems. To address the problem of high-temperature light radiation, a filtering and light compensation method was developed, using automatically controllable bandpass/lowpass filtering to reduce the intensity of radiation and adaptive compensation of light intensity with laser arrays or light-emitting diode arrays in the corresponding wavelengths to obtain clear images in high-temperature environments. By combining this filtering and compensation method with different cameras (charge-coupled devices, high-speed cameras, etc.), dynamic and static images/videos in high-temperature environments can be captured. The surface evolution process of high-temperature three-point curved specimens (high-temperature alloys, C/SiC) in an atmospheric environment can be accessed online using this method, which can capture the crack expansion process of specimens in real time and the whole process of high-temperature fracture of materials, thus providing key data for the study of high-temperature fracture behavior of materials. It can also be used to study the high-temperature non-oxidation process of materials in low-pressure and nitrogen environments.

  Aiming at the surface morphology changes caused by the oxidation and ablation of the specimen in high-temperature environments, to obtain the full-field displacement and strain, the natural texture of the surface of the high-temperature structural material was used as the feature object, and the affine scale invariant feature transformation operator with affine invariance was used as the detection image feature operator for matching before and after deformation. This method has regional scale, rotation, and affine invariance, and is especially suitable for complex conditions of ground tests. In addition, this method can be used in combination with particle tracking for ablation mobility measurements or with high-speed cameras for dynamic measurements of thermal shock processes.

(ii) An experimental method of high-temperature oxidation based on laser interference was developed; a coupled mechanical–chemical model of high-temperature oxidation was established; and a laser interference method to measure the oxide film morphology and stress in high-temperature environments was developed. To understand the growth and stress evolution of oxide films, a laser shear interferometry method was developed to measure film morphology and stress in high-temperature environments. This method can be used to identify the relationship between the interferogram phase and the sample morphology considering the temperature effect and the curvature of the film/substrate system at high temperatures, and to calculate the nonuniform stress of the film by extending the Stoney formula. This optical technique is characterized by full-field nonuniform curvature measurements and vibration insensitivity. The reliability of this method was demonstrated by measuring SiO_2 films grown on Si sheets, and it can be extended to higher temperatures, thus providing a way to measure film stresses and high temperatures. An optical interference model was developed that considers the change in the air refractive index at high temperatures, and a full-field, real-time, vibration-insensitive multi-wavelength shear interferometry method was proposed to improve the precision. Theoretically, the higher the number of wavelengths used in a shear interferometer, the higher the precision of measuring slope, curvature, and reflected surface shape. The method was calibrated using a spherical reflector with a specified radius of curvature, and the validity of the method was demonstrated by experimentally obtaining the inhomogeneous deformation and shape of the TiNi film/Si substrate system. To eliminate the effect of air convection in practical applications, the shear interferometry method was digitized, and a compensation method for the distortion caused by the change in the air refractive index was proposed. These high-temperature shear interferometry methods have become some of the main methods for full-field high-temperature stress testing of film/substrate systems.

(iii) A coupled mechanical–chemical model of high-temperature oxidation was developed. Considering the experimental phenomena and data as well as the high-temperature creep properties of metals, a coupled stress–oxidation evolution model for metallic materials was developed to capture the stress relaxation during oxidation. It was found that the oxide film stress increases sharply at the initial stage of oxidation and decreases slowly as the oxidation time increases; the maximum stress of the oxide film occurs at the initial stage of oxidation. This theory coincides with the experimental measurements. For ceramic materials, a model of oxidation kinetics and stress evolution with stress–diffusion coupling effects was developed based on the oxidation microscopic mechanism with the introduction of the stress-regulated diffusion coefficient, as well as based on the equilibrium relationship and the diffusion equation considering stress effects. Stress is generated during oxidation owing to growth strain. The stress in turn changes the mechanical–chemical potential gradient and diffusion coefficient, thus changing the diffusion process and oxidation rate. The compressive stress inhibits oxygen diffusion and reduces the oxidation rate in a short time, while the stress gradient accelerates oxidation in a long time and the tensile stress promotes oxygen diffusion. This theory can successfully explain the parabolic trend of oxide film growth and the fluctuation and release mechanism of oxidative stress. The prediction of the oxidation evolution of SiC using this model agrees well with the experimental results, which further demonstrates the validity of this model.

17 Design, Preparation and Ablation Mechanism of Ultra-High-Temperature Ceramic Matrix Composites

In the face of the deteriorating operating environment of nose cones, wing leading edges, and solid rocket motors for hypersonic vehicles, the existing high-temperature resistant materials, such as refractory metals, graphite materials, and C/C composites, are unable to meet the application requirements. Continuous fiber-reinforced ultra-high-temperature resistant ceramic matrix composites (CFR-UHT-CMCs) are one of the most promising candidates for the preparation of nose cones, wing leading edges, and solid rocket motor nozzle liners for hypersonic vehicles because of their toughness, thermal shock resistance, and excellent ablation resistance.

Among the preparation techniques of CFR-UHT-CMCs, the precursor impregnation and pyrolysis (PIP) process has a low preparation temperature and can achieve near-net molding of large complex-shaped components, while the reactive melt infiltration (RMI) process has the advantages of low cost, short cycle time, and near-net molding. However, the PIP process still lacks a particularly suitable precursor for UHT-resistant ceramics, and there have been very few research reports worldwide on the preparation of CFR-UHT-CMCs by the PIP process. Some studies on the preparation of UHT-resistant composites by the RMI process have been carried out abroad, but further research work on material systems and process optimization and mechanisms is needed. Moreover, the high-temperature performance, ablation and oxidation resistance, and related mechanisms of the prepared UHT composites also need to be studied and discussed.

In this project, the PIP and RMI processes of CRF-UHT-CMCs, the preparation of multiphase UHTC coatings, the ablation resistance and ablation mechanism of UHT CMCs, and the development of end cap scaled parts were studied. The following conclusions were drawn.

(i) A series of carbon fiber-reinforced UHT CMCs (e.g., C/SiC-ZrC, C/SiC-ZrB_2, C/C-ZrC, C/C-ZrB_2, C/SiC-ZrC-ZrB_2, and C/ZrC) were prepared using the PIP process and high-temperature RMI process. By optimizing the fiber surface coatings, components, and process parameters, we prepared UHT CMCs with good mechanical and thermophysical properties, which significantly expanded the scope of UHT CMCs. First, UHT-resistant ceramic precursors, including TiC, ZrC, and ZrB_2, were prepared using the hybrid reaction method, and the cross-linking and pyrolysis mechanisms were investigated. Among the prepared precursors, the TiC precursors and alcohol-based ZrC precursors have good cross-linking and pyrolysis properties and can meet the requirements of the PIP process. Second, C/ZrC composites were prepared using the PIP process. To improve the densification efficiency and material properties of the composites, a process of low-temperature mineralization and high-temperature heat treatment for carbon thermal reduction was identified. The optimized process parameters are as follows: cross-linking at 150 °C, mineralization at 700 °C, heat treatment at 1600 °C, and 20 PIP densification cycles; the prepared C/ZrC composites have a bending strength of 253.6 MPa, a modulus of 42.3

GPa, and a fracture toughness of 14.54 MPa·m$^{1/2}$; after 300 s of oxyacetylene flame ablation, the mass ablation rate is 0.0059 g/s, and the line ablation rate is 0.0040 m/s. Third, the interface of C/ZrC composites prepared by the PIP process was optimized to improve the mechanical properties and ablation resistance of the composites. The SiC_{PIP2}-C/ZrC composite of the PIP-SiC interface layer provides the highest overall performance, with a bending strength, modulus, and fracture toughness of 319.2 MPa, 46.3 GPa, and 18.81 MPa·m$^{1/2}$, respectively, and the mass ablation rate and line ablation rate are 0.0098 g/s and 0.0089 mm/s for the oxyacetylene flame, respectively. Fourth, the preparation of C/ZrC-SiC multiphase CMCs improved the oxidation resistance of UHT-resistant composites. The bending strength of the C/ZrC-SiC composite is 322.0 MPa, modulus 48.3 GPa, and the fracture toughness 11.55 MPa·m$^{1/2}$; its static oxidation resistance at 1200 °C is much higher than that of the C/ZrC composite. The mass ablation rate and line ablation rate of the oxyacetylene flame are 0.0089 g/s and 0.0136 mm/s, respectively, while the mass ablation rate and line ablation rate of the arc wind tunnel are 0.0181 g/s and 0.0037 mm/s, respectively. Finally, the process parameters of C/ZrC composites prepared by the RMI process were studied and optimized, and the optimal process conditions were identified: the reaction temperature was 2000 °C; the reaction time was 30 min; and the pressure was vacuum. We concluded that the C/C substrate with a density of approximately 1.40 g/cm^3 prepared by the chemical vapor infiltration (CVI) process is a good raw material; the C/ZrC composite treated at 1600 °C has the highest overall performance; and the bending strength and modulus are increased to 192 MPa and 17.7 GPa, respectively, and the mass ablation rate and line ablation rate are reduced to 0.0040 g/s and 0.0017 mm/s, respectively.

(ii) The multiphase UHTC coatings with gradient composition were prepared using the slurry high-pressure impregnation method and the high-temperature reaction method. The coating bonded well with the substrate and had an excellent ablation resistance. First, the precursor slurry containing UHTC powder was impregnated at high pressure to develop gradient UHT coatings after several pyrolysis procedures. Then, ZrB_2 and ZrC coatings were prepared on the surface of the C/SiC composite by high-temperature sintering after slurry coating with zirconium powder, boron powder and phenolic resin as raw materials. The sintering process of the coatings was investigated, and their composition, structure and corrosion resistance were characterized. The coatings prepared at 1600 °C are composed of ZrB_2 and a small amount of ZrC and ZrO_2. After 60 s of ablation in the oxyacetylene flame, the line ablation rate of the coated composites was close to zero owing to the oxidation of ZrB_2, which formed a molten layer of ZrO_2.

(iii) The ablation resistance of the UHT CMCs was evaluated by using oxyacetylene flames, plasma arcs, and arc wind tunnels; and UHT CMCs with excellent ablation performance in an oxidizing environment (line ablation rate as low as 2.7×10^{-4} mm/s) were prepared. The ablation resistances of C/ZrB_2-SiC, C/ZrC-SiC, and C/TaC-SiC were investigated in oxyacetylene flames, plasma arcs, and arc wind tunnels, respectively. UHTCs in composites play an important role in ablation resistance, and the ablation resistance of all of the above three composites is better than that of C/SiC. In the oxygen acetylene test environment, the surface temperature of the specimens is approximately 2200 °C. The mass and line ablation rates of C/ZrB_2-SiC are 0.0062 g/s and 0.0052 mm/s, respectively, while the mass and line ablation rates of C/ZrC-SiC are 0.0104 g/s and 0.0111 mm/s, respectively, and the mass and line ablation rates of C/TaC-SiC are 0.0134 g/s and 0.0187 mm/s, respectively.

(iv) The ablation mechanism of UHT CMCs in different ablation assessment environments was compared and analyzed, and the ablation model in oxyacetylene flames was established. The dynamic evolution of ablation in arc wind tunnels with different heat flux densities was elucidated, and the relationship between the components of the UHT CMCs and the ablation resistance temperature was identified.

The ablation mechanisms of C/ZrB_2-SiC, C/ZrC-SiC, and C/TaC-SiC in oxyacetylene flames were investigated. It was found that the ablation of the specimens in oxyacetylene flames is mainly thermochemical and thermophysical ablation with mechanical exfoliation. The molten oxide layer formed on the surface of C/ZrB_2-SiC at approximately 2200 °C has a high viscosity, which can resist airflow and prevent oxygen diffusion into the material, and the material shows good resistance to ablation. However, C/ZrC-SiC cannot form a viscous molten layer, which is not conducive to oxygen diffusion into the material. The melting point of TaC oxidation product Ta_2O_5 is only approximately 1870 °C, which cannot form a relatively viscous molten layer on the ablated surface or provide oxygen barrier protection for the internal structure of the material. The ablation mechanism of UHT CMCs was investigated in arc wind tunnels, where thermophysical ablation, airflow scouring, and mechanical exfoliation together determine the ablation resistance of the composites. Although the melting point of ZrB_2 is only 3040 °C, the melting points of ZrC and TaC are 3530 °C and 3880 °C, respectively. When the surface temperature of the material is 2800 °C, the exfoliation resistance of ZrB_2 is the lowest, followed by ZrC, and the exfoliation resistance of the TaC matrix is the highest.

An oxyacetylene flame ablation model for the C/ZrC-SiC composite was developed. The ablation surfaces are divided into the central molten zone, SiO_2 depletion zone and SiO_2 enrichment zone from inside to outside. Along the thickness direction, the C/ZrC-SiC composite can be divided into a molten slurry layer, a granular SiO_2 depletion layer, a molten SiO_2-enriched layer, and a non-ablative composite layer. The SiO_2-enriched layer is continuous and dense, providing protection against ablation for C/ZrC-SiC composites.

(v) Based on the research results of this project, the end cap scaled parts and sharp leading edges developed have passed the ground arc wind tunnel test and have outstanding advantages such as low ablation, oxidation resistance, scouring resistance, and thermal shock resistance.

18 Research on Toughening Mechanism of ZrB_2-SiC Ultra-High-Temperature Ceramics Against Thermal Shock

Ceramic thermal protection materials are one of the main candidates for critical hot-end components of hypersonic vehicles. However, the intrinsic brittleness of ceramics is a key issue for their engineering applications. To address the toughening problem faced by ceramic thermal protection materials, this project focused on the toughening mechanism of ZrB_2-SiC UHTC against thermal shock and mainly studied the thermal shock failure mechanism, thermal shock behavior, and crack expansion mechanism of UHTC materials. The following conclusions were drawn.

(i) A new concept and method to enhance the thermal shock resistance of ceramics by bionic design of ceramic surface structure was proposed for the first time in the world. By using the plasma etching technique and acid etching method, a superhydrophobic nanostructure imitating the wing membrane surface of a dragonfly was successfully introduced into the ceramic surface, which effectively expanded the actual surface area of the material and increased the water contact angle of the ceramic surface by more than 50°, making it a superhydrophobic surface. The results of water quenching and thermal shock experiments showed that the residual strength of conventional ceramics decreases precipitously after quenching at 400 °C, while the residual strength of the superhydrophobic nanostructures does not decrease significantly after thermal shock. This is because the ceramic surface after bionic treatment is automatically covered with an air film during thermal shock, which increases the thermal resistance of the ceramic surface by a factor of nearly 10 thousand. As a result, the thermal gradient generated by the severe temperature difference between the ceramics and the thermal shock medium as well as the resulting thermal stress can only act on the superhydrophobic nanostructures on the ceramic surface and cannot directly act on the actual parts of the ceramics. This effectively eliminates the thermal shock failure of the ceramics and results in high thermal shock resistance.

(ii) The crack distribution in the combined ceramic structure and the actual pure ceramic structure was revealed through water quenching thermal shock experiments on Al_2O_3 ceramic plates and combined plates, and the mechanism of crack expansion was revealed. In the experiment, the plates were heated to the target temperature at a rate of 10°/s and then held for 20 min before being dropped into a constant temperature water bath at 20 °C. To visualize the macroscopic crack distribution, the specimens were dried for 12 h and then soaked with a blue dye to develop the crack shapes of the two ceramic structures during quenching. The results showed that the crack shapes of the two structures differed significantly, mainly owing to the size effect of the surface cracks and the boundary effect of the internal cracks. Therefore, the structure of the combined ceramic plate cannot be used to characterize the crack shape of the overall ceramic plate.

(iii) The Biot number was derived to characterize the thermal shock sensitivity and damage process of ceramics. The relationship between the Biot number and the thermal shock performance of ceramics was analyzed. For spherical ceramics, the Biot number was used to describe the geometric and heat transfer properties, and the Fourier number (i.e., dimensionless time) was used to represent the temperature wave propagation and the duration of thermal stress during thermal shock. The relationship between the Biot and Fourier numbers of spherical ceramics during thermal shock was investigated to identify a critical Biot number that effectively determines the sensitivity of spherical ceramics to quenching; it was shown that the Fourier number corresponding to the critical Biot number can be used to determine the temperature wave propagation time and thermal stress against thermal shock. For cylindrical ceramics, when the Biot number was larger than the critical value, the thermal shock damage of the ceramic cylinder was a fast process that occured only in the initial thermal conduction state. Stress duration and geometric characteristics were crucial to the damage of ceramic materials against thermal shock, and the thermal shock failure of ceramic spheres in the heat conduction process was uncertain. This result can provide guidance for the selection of ceramic materials in thermal structural engineering, especially for thermal shock.

(iv) The physical mechanism that determines the residual strength of ceramics after thermal shock was revealed by layer-by-layer microstructure analysis of the ceramic material along the thickness direction after thermal shock, combined with statistical measurements of the density and depth of cracks generated within the ceramic material. The analysis showed that the stable tendency of the residual strength behavior of ceramic material after thermal shock is caused by the invariance of the maximum crack depth, while the crack density has relatively less influence on the residual strength. Therefore, the key factor controlling the residual strength is the maximum crack depth rather than the density of cracks in ceramics. The large fluctuations in residual strength near the critical temperature difference of the thermal shock are caused by the high randomness in the location of the deepest crack.

19 Theoretical Research on Design Optimization of Multifunctional Ultralight Structures for Near-Space Vehicles

For the multifunctional ultralight structure required for near-space vehicles, the fine modeling of the structure composed of structurally porous materials (e.g., lattice materials, honeycomb materials, and grid materials) was considered. Because the microstructure of the material is very different from the macrostructure, the workload is unimaginable if the analysis is directly based on the smallest-scale structure. The optimal design of such a structure may contain tens of thousands of design variables; given limited resources, a simple “brute force” solution may result in the corresponding multiscale material/structural optimization problem not being computable (as the computational complexity is computable). Therefore, integrated structural and material design and hierarchical structural design need to be optimized. Since aerospace vehicles are mostly of thin-shell structures, to meet the structural strength and reliability requirements, specific structural elements must be placed in the connection area to disperse the concentrated loads to be transferred, and the effect of this concentration diffusion directly affects the failure behavior and reliability of the structural strength. The topology optimization of the structure and an optimal design model of the concentration diffusion structure are needed. In this project, the following conclusions were drawn with respect to the optimal design of ultralight hierarchical structures, the preparation and mechanical property analysis of typical lattice cylindrical shells, and the topology optimization of structures considering concentration diffusion.

(i) The theory of lightweight material–structure integrated design and design optimization of hierarchical structures was developed, and the coupling of two geometric scales of material/structure was enabled based on the progressive homogenization theory for structures composed of ultralight porous materials. A PAMP model with concurrent material/structure multiscale geometry was proposed, deepened, and expanded, and a theoretical framework was established for the realization of lightweight porous materials and structures with concurrent multiscale geometry, as well as the mathematical formulation and numerical implementation techniques for the corresponding problems. The technique of sensitivity transfer between different material/structure levels was developed, breaking the limitation that the classical SIMP model (for solid materials) in the field of topology optimization cannot realize the topology optimization of structures composed of porous materials, and the computability of the concurrent multiscale material/structure optimization problem was significantly improved.

(ii) A double-skin sandwich cylindrical shell sample of the carbon fiber-reinforced composite Kagome lattice was prepared using the winding method and secondary molding process. In a compression test using the true three-axis rigid servo testing machine, Instron 8506, the load capacity and stiffness of the sandwich cylinder were 524.6 kN and 161.8 kN/mm, respectively. Meanwhile, a single-skin triangular sandwich cylindrical shell prepared by Japanese scholars (with the same dimensions and a slightly heavier weight) only had a reinforced cylinder load capacity of 116.9 kN and an initial stiffness of 10.6 kN/mm, which eventually reached 28.2 kN/mm. The stiffness and strength of the double-skin sandwich cylindrical shell sample prepared in this project were both much higher than those of the single-skin triangular sandwich cylindrical shell. The significant increase in load capacity and stiffness was attributed to the restraint of the double skin on the lattice; the double-skin design effectively inhibited lattice buckling, thus eliminating the dominant damage mode. In the experiment, we observed that skin and strength damages were the competing damage mechanisms for the lattice sandwich cylinder and that overall buckling, single-skin single-cell buckling, and strength control failure all contributed to the failure of the sandwich cylinder. The absence of delamination between the skin and lattice in the experiment indicated that the secondary coreinforcement method ensured the bond strength between the skin and lattice core. This new sandwich structure could exploit the high strength and stiffness of carbon fibers, demonstrating the potential of lattice composites to improve mechanical properties. Meanwhile, the lateral and longitudinal fundamental frequencies and vibration modes of the lattice sandwich bearing cylinder were measured under different boundary conditions, and the influence of boundary conditions and additional mass on the vibration performance of the lattice sandwich bearing cylinder was investigated to provide experimental data for validating the theoretical model.

(iii) With respect to the concentration diffusion phenomenon in complex structures of carrier aircraft, a topology optimization model for designing structures with concentration diffusion was established based on continuum topology optimization. The objective function is the minimum flexibility of the structural system comprising connectors and supports, and the optimal distribution in the connector domain was found by considering the material usage constraint in the design domain and stress uniformity constraint (i.e., the constraint based on certain material usage and the variance of the nodal forces in the specified connector section) in the examined area (load-bearing structure). Based on the SIMP model, the objective function, constraints, and corresponding sensitivity values were calculated, and the optimization problem was solved using mathematical programming methods, such as the method of moving asymptotes. To avoid numerical instability such as checkerboard in optimization, linear filtering of the improved density was needed. Two different optimization cases in planar and 3D were given using the model, and reasonable optimal design results were obtained in both cases.

Based on this, the redundancy or failure of the "radial rib" structural design, which is widely used in the short shell of the launch vehicle fuel tank, will bring unnecessary weight gain to the main structure. A feasible conceptual design scheme of the structure was proposed, considering the actual forces and constraints of the engineering practice. First, a conceptual design was developed through topology optimization, and the shape and dimensional optimization methods were further applied based on topology feature extraction to develop a refined solution that meets all design requirements. The conventional "short box and short shell" could be regarded as a single-level "radial rib" design with equal cross-sectional dimensions. Then, the multilevel "radial rib" structural design was proposed and topologically optimized, although the results showed that the optimized structural design could not achieve effective concentration diffusion. The cross-sectional force peaked at multiple places in the examined area, which was much higher than the average value. However, for the optimal design of a two- or three-level "radial rib" structure, the cross-sectional force in the examined area was close to the average value, indicating that the multilayer bifurcation characteristic of the graded "radial rib" structure was favorable for uniform concentration diffusion. Under the same structural weight conditions, all three optimization schemes met the strength and stability requirements of the structural design. Compared with the conventional design, the maximum cross-sectional force was reduced by 30.1% for the single-level optimal design, and the two- and three-level optimal designs had even greater reductions of more than 45%. In addition, the variance of the cross-sectional force significantly reduced for the three optimal designs, with the two- and three-level optimal designs having a reduction of over 80%. In terms of the concentration diffusion effect, the three-level structure was superior to the two-level structure and considerably better than the single-level structure; however, the increase in the number of levels increased the structure's complexity.

To facilitate fabrication, the optimal design scheme of the two-level "radial rib" structure was recommended. In this scheme, the bifurcated "ribs" on both sides of the structure enhanced the ability to transmit the concentration along both sides and reduce the peak cross-sectional force; the small bifurcated "ribs" near the examined area allowed the concentration to eventually spread almost uniformly to the lower end of the load-bearing structure. Therefore, the established optimal design method for concentration diffusion has clear engineering significance: not only has the resulting new member design been used by design departments for reference but also the innovative design process of "conceptual design–result interpretation–refined design" can be applied to other engineering structure optimal designs.

20 Research on the Preparation Technology of Ultra-High-Temperature, High Thermal Conductivity, Non-ablative C/C Composites and Their Thermal Protection and Response Mechanisms

China is a latecomer to HTC mesophase pitch-based carbon fiber research, and the progress is relatively slow. Therefore, there is a large gap in research depth and breadth between China and advanced countries in this field. In particular, our R&D of HTC ribbon-shaped cross-section carbon fibers and their C/C composites still remain in the initial stage. Owing to the strategic relevance and broad market prospects of this material in modern industry, national defense, and high technology development, foreign countries have imposed a strict embargo on the export of HTC carbon fibers, and there are few reports on the preparation technology and production equipment of HTC ribbon carbon (graphite) fiber. Thus, in China, the R&D of HTC functional materials is urgent. As such, this project focused on preparing UHT, HTC, and non-ablative C/C composites as well as their thermal protection and response mechanisms. The main findings are as follows.

(i) A naphthalene-based mesophase pitch (AR, MP-H) produced by Mitsubishi Chemical Corporation was used as the raw material. The optical texture of the mesophase pitch raw material after being melted at approximately 330 °C and cooled had a typical wide-area streamlined structure. The width of the streamline area was uniform; the degree of order was high; the overall orientation was good; and the optical anisotropy content was as high as 100%. After melting, the overall wide-area streamlined structure of the mesophase pitch was perfected with a higher degree of orientation. Then, the pitch-based fiber was prepared on an independently designed microcomputer numerical control pitch-based fiber spinning machine. The spinning process conditions (e.g., spinning temperature, spinning pressure, and winding speed) were adjusted using a circular spout with a diameter of approximately 300 μm to produce a ribbon-shaped pitch-based fiber with a smooth surface, a controllable width of 0.3–1.5 mm, and a thickness of 15–30 μm. During the subsequent high-temperature carbonization and graphitization heat treatment, the ribbon-shaped fiber maintained its shape without splitting, wrinkling, or crimping, which effectively solved the problem of the easy splitting of radial circular cross-section fibers and realized the preparation of HTC pitch fiber with a highly oriented wide-area structure (the width was greater than 1 mm).

Through the analysis of the oxidation and mechanical properties, it can be seen that during the oxidation and stabilization process of the ribbon-shaped pitch-based fiber at 220–260 °C, the pitch macromolecules formed a cross-linked structure under the effect of oxygen, and a relatively good infusibility effect was achieved, which “fixed” the shape and structure of the ribbon-shaped fiber, whereas the oxygen-containing functional groups generated, such as carboxyl groups, carbonyl groups, and ethers, disappeared during the subsequent high-temperature heat treatment. With an increase in the heat treatment temperature, the diffraction peak of the (002) crystal plane of the ribbon-shaped carbon fiber gradually strengthened; the peak shape became narrower and sharper, the crystallite size gradually increased, and the layer spacing of the (002) crystal plane continued to decrease. Compared with the low-temperature carbonization of fiber, the crystal growth and development inside the graphitized fiber was complete; the 3D orderly stacked structure was obvious; and the graphite layers had a relatively high degree of preferred orientation along the main surface of the ribbon-shaped fiber. The mechanical performance of the ribbon-shaped pitch-based fiber, ribbon-shaped preoxidized fiber, and ribbon-shaped fiber after low-temperature (400–700 °C) heat treatment was relatively low. The tensile strength and elastic modulus of ribbon-shaped fibers carbonized at 1000 °C were 0.876 and 109 GPa, respectively; the mechanical properties of graphitized ribbon-shaped fibers carbonized at 2000 °C significantly improved, and the tensile strength and elastic modulus were 1.28 and 183 GPa, respectively. After the graphitization temperature was increased to 3000 °C, the tensile strength and elastic modulus of ribbon-shaped fibers reached 2.53 and 421 GPa, respectively. The higher the heat treatment temperature is, the higher the crystallinity and graphitization degree of the ribbon-shaped fiber, and the better the oxidation resistance. The oxidation resistance of graphitized ribbon-shaped fibers was significantly better than that of carbonized fibers. The oxidation resistance of the graphitized ribbon-shaped fiber at 2800–3000 °C was significantly better than that of the K-1100 graphite fiber.

(ii) The prepared ribbon-shaped fiber was completely oxidized and stabilized to fix the ribbon shape of the fiber and the preferred orientation of the mesophase pitch macromolecules. Then, moderate heat treatment was performed to improve the mechanical properties of the ribbon-shaped fiber to realize a certain strength and flexibility for easy handling. Afterward, the orderly arranged ribbon-shaped fiber was used as the matrix material to uniformly coat an appropriate amount of mesophase pitch binder on the surface, and medium temperature (500 °C) was used for the one-time hot-pressing process to prepare a 1D carbon fiber C/C composite material. Finally, high-temperature carbonization and graphitization were performed to develop an HTC C/C composite material with highly oriented graphite crystals along the length of the ribbon-shaped fiber. The volume density of C/C composites graphitized at 3000 °C exceeded 1.86 g/cm^3; the resistivity at room temperature along the length of the fiber was less than 1.5 $\mu\Omega\cdot$m; and the thermal conductivity and thermal diffusion coefficient at room temperature exceeded 800 W/(m·K) and 600 mm^2/s, respectively, which reached a leading level compared with similar materials in the world. This process overcame the difficulty of controlling the cross-linking in the moderate oxidization of pitch-based fibers in the self-adhesive molding process and solved the problems of deformation and cracking that often occur in the molding process of unidirectional C/C composites, especially for large-size samples. It also simplified the repetitive impregnation–carbonization–graphitization process in the conventional C/C composite preparation process, significantly reduced the production cost and shortened the preparation cycle, and suggested a new possible approach for preparing HTC mesophase pitch-based C/C composites. Additionally, solid infiltration and slurry coating methods were employed to develop oxidation-resistant coatings on the surface of C/C composites that could be used in UHT environments.

(iii) High-temperature oxidation-resistant coatings for HTC C/C composites with significant differences in linear expansion coefficients in different directions were developed, and the matching design and microstructure control methods of HTC C/C composites and UHT oxidation-resistant coatings were explored.

(iv) The thermal protection and response mechanisms of oxidation-resistant HTC C/C composites were initially explored by analyzing the response of conventional non-ablative C/C composites and the UHT, oxidation-resistant, HTC C/C composites studied in this project in the same environment.

21 Research on Material–Structure Integration and Thermal Protection–Insulation Integration for Near-Space Hypersonic Vehicles, and Multiparameter Experimental Integration Methods and Technologies for High-Temperature Thermal Protection Materials and Structures in Ultra-High-Temperature Oxidation Environments

This project focused on solving the key common problems in material–structure integration and thermal protection–insulation integration through multidisciplinary intersection and complementary advantages, and it further developed multiparameter experimental integration methods and technologies for high-temperature thermal protection materials and structures. Concerning material design, performance testing and characterization, designing is no longer limited to micro-, meso-, or macrolevels but starts from atoms and molecules, from designing structures based on material limitations to designing materials based on structural requirements, and from single load-bearing and thermal protection structures to integrated thermal protection/load-bearing and multifunctional structures. In testing and characterization, more attention was given to high-temperature testing methods for composite components, properties under complex stresses or combinations of loads, new thermal protection materials, as well as the scientific significance and validity of high-temperature testing methods. The analysis methods focused more on multiscale–multifield coupling, multifield modeling, high-temperature gas effects, nondeterministic analysis, and virtual testing. The main conclusions of this project are as follows.

(i) The correlations between different material and structural properties were identified at both the material and structural levels, and the thermal protection–insulation performance of materials used in the thermal protection system was considered comprehensively. Aiming at lightweight thermal protection, the optimization target was mass per unit area; the structural parameters were optimization variables; and various functions in the service process served as design constraints. The response pattern of the comprehensive performance of thermal protection was analyzed, and an integrated thermal protection–insulation design, as well as a comprehensive performance analysis method, was developed.

(ii) The application of multiscale design and multiobjective optimization in material and structural design for thermal protection was collaboratively studied. For the integrated structural/thermal protection solution, the main research objective was the integrated thermal protection of corrugated sandwich and web reinforcement. First, a size optimization design model of the integrated thermal protection structure was established, and the limit state response characteristics of the integrated thermal protection structure were analyzed. Second, based on genetic algorithms, a method for solving the optimal design problem of integrated thermal protection was developed. Finally, the developed method was employed to solve the optimization problem of integrated thermal protection with web reinforcement, and its solution was compared with the classical corrugated sandwich integrated thermal protection solution. A method of thermal–mechanical coupling optimization based on genetic algorithms and a method of thermal–mechanical coupling optimization design of thermal protection systems based on topology optimization were developed. As a result, the cooperative mechanism and design method of thermal protection, mechanical transfer and load-bearing were developed by considering thermal/mechanical matching.

(iii) Several advantageous achievements were integrated to develop representative thermal protection scheme design methods and implementation technologies. Key problems, such as material system design, structural connection, transition, matching, and process realization, were solved. Design verification and matching tests were completed, providing a new technical approach for the future development of hypersonic vehicles.

(iv) Based on the understanding of the mechanical behavior of typical thermal protection composites in high-temperature oxidation environments, various high-temperature and complex loading test methods were developed and integrated; thermal protection composite response analysis models were established from different time/space scales; and methods to collect and characterize the thermal response and field information of high-temperature structures were developed to further reveal the mechanism of heat-induced material damage and failure, as well as thermal–mechanical–oxidation coupling.

(v) The experimental techniques of force, heat, oxidation, and other key parameters in the multifield coupled service environment were developed, and the test system and loading device for simulating the multifield coupled service environment were developed. The research results provide essential experimental support for the performance characterization and structural design of thermal protection materials in a multifield coupled service environment.

(vi) Based on the analysis of the progressive damage of materials influenced by thermal–mechanical coupling, the meso analysis model considering the mesostructure properties and characteristics was embedded into the macrostructure analysis, which solved the problem of data transfer between meso-damage evolution and macroproperties and developed a multiscale analysis method for the structure of thermal protection composites, providing an approach and computational strategy to enable the multiscale and multifield simulations of materials.

(vii) The physical–chemical behavior and failure mechanism of thermal protection materials in the complex UHT environment were studied, and the strong coupling between the aerothermodynamic environment and UHTC materials and their main control factors were identified. The oxidation mechanism, performance prediction, and oxidation suppression methods of UHTC materials were developed. Using ultrasonic microcomputed tomography, high-precision observation and quantitative characterization of the internal defects of UHTC materials were realized, and toughening design and realization methods of UHTC materials were proposed. A UHTC material system suitable for different hypersonic long-duration non-ablative service environments was developed.

(viii) In the modeling and simulation process of structural analysis, the nondeterministic nature of the input parameters and physical process was assumed and approximated, which led to nondeterministic structural analysis results. Meanwhile, there were some measurement errors in the test results owing to limited sensor precision and the fact that the controlled test conditions differed from the ideal conditions. Considering the randomness of the existing service environment and material properties, multiscale and uncertainty theories and methods were introduced into the design, optimization, and evaluation of thermal protection materials and structures, and a nondeterministic analysis method was developed. The optimal design method of the thermal protection system based on the reliability index was developed; also, the failure probability and reliability sensitivity were specified to provide strong support for the optimal design.

Outlook

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1 China's Research Inadequacies and Strategic Needs

1.1 Research Inadequacies

(1) Huge gap in the knowledge reserves of basic hypersonic studies

In the past decade, China has made remarkable progress in the field of near-space hypersonic vehicles, which has attracted considerable attention globally. With strong national support, large-scale research facilities at an internationally advanced level have been established, and various key technology challenges have been overcome through enhanced integrated innovation capability; also, comprehensive and systematic deployment of basic studies have been conducted. However, compared with the decades of R&D history and technological reserves of the U.S. and Europe, between whom and China, there remains a huge gap. First, concerning research philosophies, based on long-term experience accumulation and numerous flight tests, other countries focus on the physical phenomena or effects with the most significant impact and strongest demand as well as how to improve cognitive and control capabilities, how to improve models and methods via the perfection of cognitive capabilities, and how to recognize and control new effects through continuous improvement of tests and simulations. The breakthroughs and achievements of their basic research could directly impact or be applied to engineering practice. In China, owing to insufficient accumulation in this field, it is difficult to control the key physical effects, models, and parameters. Furthermore, numerical simulation methods lack effective verification and validation means. The test methods are mainly used for verification and validation, and conventional aircraft design concepts still dominate the field. At present, the mission and R&D approaches of China significantly differ from those of other countries, and basic research has to undertake multiple missions, such as filling gaps and strengthening weak links. Thus, there is a huge gap between the basic research in China and that in other countries in terms of basic understanding, engineering concerns, research hotspots, and future priorities. To succeed in both

S. Du (ed.), *Key Basic Scientific Problems on Near-Space Vehicles*, Reports of China's Basic Research, https://doi.org/10.1007/978-981-19-8907-0_4

ground tests and flight tests, it is necessary to fully understand the strategic position and role of basic research, continue to enhance basic research, build up our strengths, and expand our scope of research.

(2) Rarity of original directions and achievements in basic hypersonic research

After nearly a decade of efforts, the direction of China's basic research has gradually shifted from following international hotspots to focusing on major national needs. Although the number of innovative achievements has gradually increased, to a certain extent, there are still problems, as some projects have been poorly targeted, homogenized, or fragmented. The Plan has performed enormous orientation work in terms of proactive layout, and the range of applications, number of applications, and understanding of key scientific issues reflect the current situation of basic research in this field in China at this stage. From a high level, we proposed revolutionary research directions, produced original results, and showed our strengths to the world but achieved few original results. The multifaceted reasons include the positioning of engineering requirements and basic research as well as the mechanisms and systems that encourage innovation. Concerning science and technology, we need to understand the needs and applications in depth, gain timely insights into the development of multidisciplinary frontier directions, improve the ability to extract the cores from scientific problems, break through conventional thinking restrictions, and solve problems with confidence.

(3) Interdisciplinary and integration abilities to be further improved

Interdisciplinary efforts are the most effective strategies to improve cognitive and innovative abilities in response to the current trends of scientific and technological development. Since the establishment of the Plan, we have been encouraging integrated innovation, thereby promoting interdisciplinary efforts in various forms, such as key projects and integrated projects, within and among the four key scientific issues and have achieved fruitful results. However, compared with other countries, there is still a huge gap in research depth and breadth, as well as difficulty in meeting the development requirements of hypersonic vehicles. For example, the Department of Mathematical and Physical Sciences has applied for 385 projects, the Department of Engineering and Material Sciences for 151 projects, and the Department of Information Sciences for 57 projects, while the Department of Chemical Sciences has applied for only six projects, yet none were funded. However, other countries have recently emphasized further collaboration between conventional hypersonic disciplines and disciplines such as chemistry, information, and mathematics. The reasons for this contrast are threefold: the restricted thinking of conventional single-disciplinary basic research, the lack of understanding of the multidisciplinary nature in scientific problems, and the need for improved collaboration and sharing mechanisms.

(4) Insufficient ability to combine basic research and flight tests

Since there are many unknown and uncertain factors in hypersonic flight, it can be difficult to reproduce the flight environment with ground tests, and there are many limitations in numerical methods. To make further revolutionary breakthroughs in hypersonic technology, flight tests have become the most critical research tool and are directly related to the breakthroughs in basic research. Flight tests can not only help us identify and understand key physical phenomena in real-life environments but can also verify the accuracy of the knowledge and methods developed through numerical simulations and ground tests, thereby providing a means to study scale effects. The U.S., Europe, Australia, and Japan are paying increasing attention to flight test programs aimed at scientific research and have achieved significant results, such as the HIFiRE program's first capture of hypersonic flight data showing shock wave interference instability, which will trigger a new scientific paradigm for hypersonic flows. Most flight tests in China still focus on system or capability verification, making it difficult to achieve mutual promotion between basic research and engineering practice. Fortunately, many flight tests of major engineering projects have gradually focused on the relevance of basic research, and the successful operation of the near-space science and technology flight test platform serves as a good start.

1.2 Strategic Needs

"To explore the vast cosmos, develop the space industry and build China into a space power is our eternal dream," stated President XI Jinping. Hypersonic technology not only significantly improves human's ability to enter, control, and explore space but also plays a key role in the systematic development and usage of near space, which has a revolutionary impact and significant application value for future national security and political and economic interests.

Long-duration hypersonic gliding/cruising/maneuvering in the atmosphere is a hotspot and trend in the development of many new aerospace vehicles, which can not only increase flight speed and maneuverability but also change many conventional concepts. Reusable transportation spacecraft are the most effective technology to reduce the cost of space transportation and increase the reliability and multimission capability. Meanwhile, as a key enabling technology covering the entire aerospace domain, the near-space hypersonic technology has a dramatic impact on future national strategic needs, such as manned spaceflight and deep space exploration.

It has been nearly 80 years since the Sänger spaceplane. The phrase "hypersonics is the future, but it may always be the future" accurately reflects the enormity, challenge, and long-term nature in the development of hypersonic technology. The greatest challenge for hypersonic vehicles comes from the limited resources for basic research, while the potential impact is enormous [1]. The key scientific and technical problems of the two types of hypersonic vehicles are shown in Fig. 1.

The U.S. Air Force has summarized the scientific and technical aspects of gliding and cruising vehicles based on the relationship between the Mach number of flight and the degree of high-temperature nonequilibrium effects in the context of developing near-space hypersonic technology. With the breakthroughs in key technologies of scramjet engines and successful flight tests, hypersonic cruise flights below *Ma* 10 mainly face the challenge of system integration, i.e., problems brought by

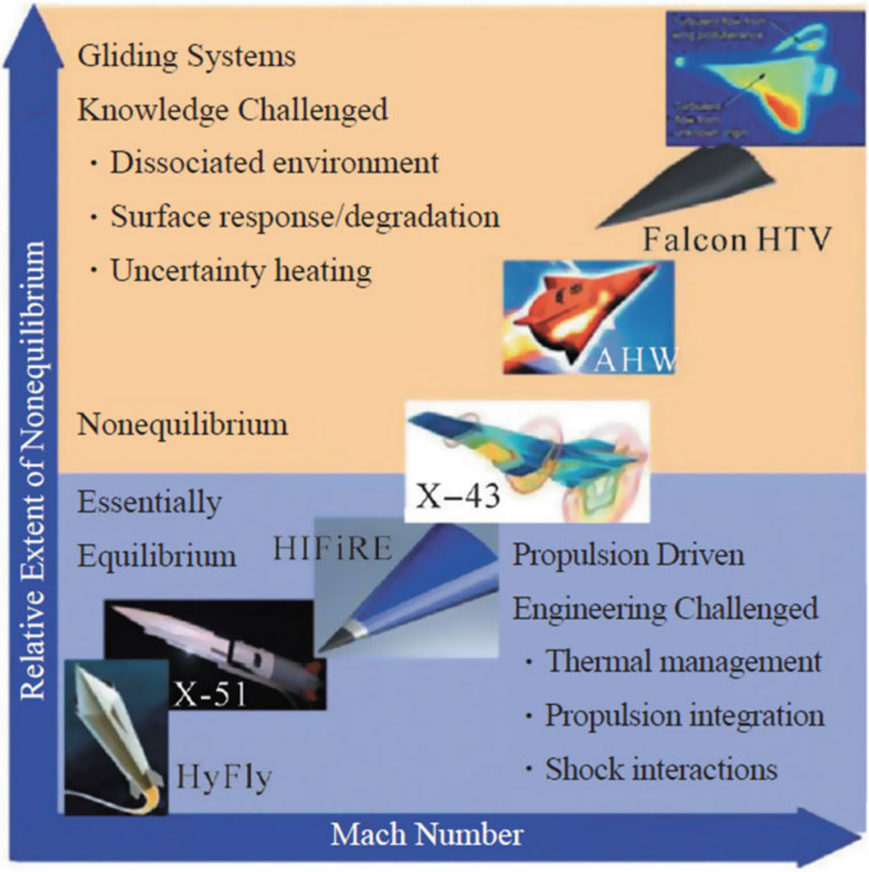

Fig. 1 Key scientific and technical problems of two types of hypersonic vehicles

the integration of the air-breathing propulsion system, including the understanding of the laminar–turbulent rotation, unsteady shock wave interference characteristics, and thermal management problems. The freestream Mach number of such vehicles is usually relatively low, and the thermochemical nonequilibrium effect is insignificant. In contrast, high-Mach number boost-glide vehicles face the scientific challenges caused by a yet unknown aerothermodynamic phenomenon, i.e., problems brought by thermochemical nonequilibrium in the dissociated environment of shock waves in high-Mach number flights. The thermochemical process determines the internal state of excitation, release of energy to generate thermal energy, and precise prediction of aerothermal/mechanical phenomena. It requires incremental improvements through simulations with increased accuracy regarding reaction rates; the interactions between the nonequilibrium environment and material surface reactions also present challenges, as the predictive capability relies on the accurate identification of the underlying thermochemical reaction rates, including the gas, gas–surface interfaces, and areas near the material surface. Many advances in aerothermodynamics are based on new insights into the conversion between kinetic, internal, and chemical energy modes. Knowledge of the dominant energy conversion mechanisms may be used to propose revolutionary approaches to achieving control of macroscopic mobility; flow fields may be designed to facilitate mechanisms for optimal energy conversion to achieve optimal flow state applications; and new approaches to flow control may emerge.

Although the breakthroughs in scramjet engine technology are encouraging, it is imperative to recognize that current missile-scale hydrocarbon-fueled scramjet engines are mainly single-use structures and capable of life prediction based on load stacking. Future needs include improving the performance and efficiency of scramjet engines, broadening their operating Mach number ranges, solving various problems owing to upscaling, developing reusable hydrocarbon-fueled scramjet engines and combined cycle engines, gradually improving the aero-propulsion integrated design and analysis methods for a sustainable high-speed cruise, as well as discovering and exploring new propulsion concepts and physical models.

The special requirements for "weight reduction" of near-space hypersonic vehicles have made synergistic demands for material and structural lightweight, extreme-environment resistance, and multifunctionality, especially for specific performances such as specific strength, stiffness, volume, energy, and power. Therefore, there is a need to develop higher-performance structural/functional materials, explore more efficient structural concepts and couple more functions through structural design to achieve weight reduction. The next-generation composites should focus on multifunctional drive designs, with the potential of reducing cost and manufacturing energy by 50% and 75%, respectively. Material design and microstructure control have penetrated the nanoscale and will significantly improve the performance and functionality of materials. To transfer the revolutionary properties of nanostructured materials into macroscale main load-bearing structures is a major current task, and to withstand the extreme service conditions owing to hypersonic vehicle aerodynamic loads and propulsion systems remains the most critical issue for high-speed vehicle development. Considering further exploration of the potentials, we need to consider the coupling mechanism between the service environment and material response, with a focus on the far-from-equilibrium states, surface damage, damage with energy rate changes, and dynamic interface of materials, which are crucial for research on aerothermal protection, in-engine protection, and energy-containing materials.

The control of near-space hypersonic vehicles is a passionate challenge that includes the consideration of physical constraints, propulsion altitude nonlinearity, strong coupling between thrust and altitude, nonminimum phase behavior owing to control surface dimensions, and analysis of high uncertainty owing to unknown aerodynamic–thermal–kinetic behavior. Despite these technical challenges, we must also face the difficulty in reproducing service conditions in ground facilities. Whether by using classical control design methods in the frequency domain and control design knowledge models based on physical models or by using nonlinear dynamics inversion control methods similar to those used for aircraft, it is difficult to overcome the difficulties in hypersonic vehicle control designs, such as the inverse instability dynamics, global (semiglobal) solutions of robust properties, and physical constraint compliance of vehicle integration. New theories and methods should be developed.

2 Conceptions and Suggestions for Further Research

2.1 Conceptions

Considering the current global situation and development of near-space hypersonic vehicles, national needs, and scientific development needs, as well as the research results of the Plan, the Steering Committee believes that in basic hypersonic research at the national level, we should continue to deepen the research of key scientific issues in the framework of the established basic research systems and strengthen the support for problem-driven interdisciplinary collaborations and original studies. The basic problems or research directions that should be focused on are as follows.

First, we need to improve our understanding and control of the special physical effects of hypersonic flight, especially various problems and challenges in the fields of aerodynamics, propulsion, materials and control brought by "high energy" and "extreme heat." Boundary layer transition of hypersonic vehicles, which significantly increases the surface heating rate and aerodynamic drag, is still a complex and poorly understood physical phenomenon; and improvements in the ability to predict or delay transition and maintain laminar flow will play a paramount role. Shock wave interactions pose ubiquitous challenges for high-speed vehicles, as they create extreme local conditions that make it difficult to predict the associated thermal and noise loads. Therefore, accurate predictions are critical for basic research and engineering applications. The greatest challenge posed by rate-dependent nonequilibrium flow, the most typical feature of hypersonic flight, is the loss of existing predictive capabilities owing to increased chemical complexity, thus requiring enormous efforts to reduce reaction and rate uncertainties, enhance interdisciplinary collaborations with disciplines such as chemistry, and understand more transient phenomena or effects. Unsteady separation will cause an increase in thermal load, produce strong wall pressure fluctuations, and stimulate aircraft panels to resonate. How to consider and grasp the fatigue load from an unsteady separation becomes a crucial factor in design refinement.

Although the feasibility of the scramjet engine was successfully demonstrated in flight tests, there are still many scientific and technical challenges in terms of availability, practicality, and reusability. We need to further understand the mechanisms of supersonic combustion; provide the basis for developing ignition, propagation, and steady combustion mechanisms and methods with a wide range, high robustness, and high efficiency; actively explore new approaches to improving drag reduction, mixing efficiency, combustion efficiency, and engine efficiency; and solve the synergistic problems between efficient fuel cooling and engine thermal protection. The focus is on the scale effect of large-scale scramjet engines, the cycle mode and modal transition mechanism of combined cycle engines, new techniques of continuous adjustable inlet/exhaust, and optimal design methods of rotating detonation engines. Additionally, we need to develop high-confidence numerical simulations, experimental simulation methods, and diagnostic techniques that can improve the above capabilities.

Materials for extreme service environments and lightweight structures are still the most fundamental control factors affecting hypersonic vehicle development: they are the constraints of the trajectory of Sänger, the prerequisites for the trajectory of QIAN Xuesen, the cause of HTV-2 failure, and the biggest shortcoming of hypersonic engineering. Therefore, it is necessary to utilize tools such as integrated computational materials engineering (ICME) to improve our understanding of the mass transfer kinetics of the thermal, chemical, and mechanical stability of UHT materials, chemical reaction paths, and deformation mechanisms to develop bottom-up design methods for special materials, study far-from-equilibrium material behavior, employ new methods (e.g., low dimensionalization, artificial structuring, integration, and intelligence), perform compounding and interface control at microscales, and fabricate high-performance materials with new effects. We need to focus on the scientific aspects of joining, assembling, insulating, and sealing material structures and consider the survivability of new types of directed energy against extreme environments. Other crucial actions include considering the multifield coupling and nonlinear effects of the local response of hypersonic vehicle structures, integrating our understanding of material performance evolution into structural scale simulations, developing multiscale failure simulation methods in a nondeterministic framework, establishing structural dynamic response analysis and life prediction methods with combined or coupled loads, and improving the modeling, failure, and life prediction capabilities of thermal structural composites, new load-bearing thermal protection systems, and active–passive thermal protection systems.

Most control theories and methods related to hypersonic vehicles have been validated and refined in many flight tests, but there is still a long way to go to fulfill their multiple missions. For hypersonic vehicles with increasingly defined structural and application characteristics, it is necessary to improve the integrated modeling capability of structural, flight, and orbital control, and continuously enrich its interdisciplinary modeling capabilities. For special requirements, such as unstructured environments and nonlinear response characteristics, it is necessary to develop multivariate, hybrid, and heterogeneous control system designs and stability analysis methods. We need to combine advanced sensors, actuators, and information processing technologies to enhance intelligent decision control capabilities, such as real-time fault diagnosis, dynamic route planning, autonomous target selection, threat avoidance, and mission reconfiguration. We also need to explore adaptive control and decision-making methods in uncertainty, information redundancy, dynamic changes, damage tolerance, and network environments through organic combinations of information science, mathematics, materials, aerodynamics, and structural dynamics.

In addition, the role of advanced testing techniques, numerical simulation methods, and flight tests in basic hypersonic research should be fully recognized. Nonperturbative extreme-environment-resistant diagnostic instruments and testing techniques should be developed for hypersonic ground and flight tests to accurately sense aerodynamic/thermal, propulsive/thermal, mechanical, and noise loads and responses. Thus, we can achieve nonperturbative nondestructive sensing and observation of far-field, near-field, surface and subsurface physical effects, as well as adapt to the special requirements of thin-walled structures with high thermal gradients, large temporal- and spatial-span boundary layer transitions, complex structural areas, and inlets. We should focus on calculation methods and techniques that can provide accurate, reliable, and efficient analysis for complex system designs as well as continue improving multiscale modeling (material, structure, plasma, flow, and combustion), multiphysics field modeling (flow/solid), uncertainty quantification, uncertainty optimization, and control in an interdisciplinary framework. We will continue to emphasize the role of uncertainty quantification, verification and validation, as well as understand the impact of dispersion on analytical reliability and computational precision. Considering the limitations of ground-based and numerical simulation tests, clear scientific experimental objectives need to be proposed; for specific physical effects, effective payloads will be designed by combining carrying flight or creating flight test conditions, which helps to understand key physical effects or verify paramount theories, models, and methods.

2.2 Suggestions

With the support of the two major research plans successively established by the NSFC, basic studies on hypersonic technology have been continuously funded and steadily developed for nearly 15 years. They have comprehensively enhanced the overall capability of basic research in this field in China, strongly supported the breakthroughs of key technologies for major national needs, especially laying a solid foundation for sustainable development, and achieved remarkable results. However, after nearly 80 years of arduous development, hypersonic technology still faces many scientific and technical challenges and requires long-term stable and targeted basic research investment and support. The history of hypersonic development shows that there is no greater setback than the dissolution of the scientific and technical groups with the latest knowledge and development experience when a project comes to an end. Therefore, there is a need to ensure that the groups stay together and that the research continues through a combination of problem-driven approaches, continued major plans or projects, and framework agreements with the industrial sectors and clients.

The current national scientific and technical system reform has created a strong need for building basic and innovative capabilities. While encouraging free exploration and enhancing the source innovation capability, basic studies of near-space hypersonic vehicles need to clarify their status and positions in the entire chain of advanced exploration, key technology research, and application demonstration, encourage sublimation from natural sciences to technical sciences, concentrate on major national strategic tasks, and give full play to its role in conceptual and technological innovation. It is necessary to have the mentality of "sharpening a sword for 10 years" and strengthen the concept of proactive transformation.

The dual nature of mechanics is the main reason for its vital importance in understanding and transforming the world. In addition, it is crucial to understand the essence of mechanics and identify its patterns to create an organic synergy between fundamentals and techniques. The discipline of mechanics plays a leading role in the Plan, and the key theories and methods of hypersonic vehicles are most likely to be the main direction and good opportunity for mechanics to make breakthroughs and achieve success in both ground and flight tests. Therefore, it is necessary to enhance our ability to accurately extract scientific problems from engineering requirements, thoroughly solve them, and apply the solutions to engineering practice. Meanwhile, it is necessary to develop innovative concepts and technologies and cross the "Death Valley" of innovation, to which the key is developing theories and methods that can be applied in real world conditions and discovering major revolutionary theories that will revolutionize conventional theories.

Hypersonic technology is interdisciplinary and strongly coupled, and many scientific and engineering problems in this field require deep integration within the discipline of mechanics and proactive combination with other disciplines. There is a need to continue developing and exploring new funding models and management systems for relevant basic studies, such as the existing key projects and integrated projects, or establishing more interdisciplinary projects. An alternative means is to learn from others' funding methods, such as the MURI program in the U.S. By all means, we need to enhance the ability to think interdisciplinarily and systematically, intensify the collision and integration of ideas among researchers, and attract more high-level talent to join in basic hypersonic research. Additionally, we need to further encourage conceptual innovation, improve our ability to identify and gain insights into the application of frontier and emerging technologies, explore the potentials and feasibility of nanotechnology, additive manufacturing, flexible electronics, quantum computing, big data, and other hotspots in the breakthroughs of core hypersonic scientific problems, propose leading and innovative research directions, be aware of Pasteur's quadrant, and actively promote the transfer of research findings into practice.

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