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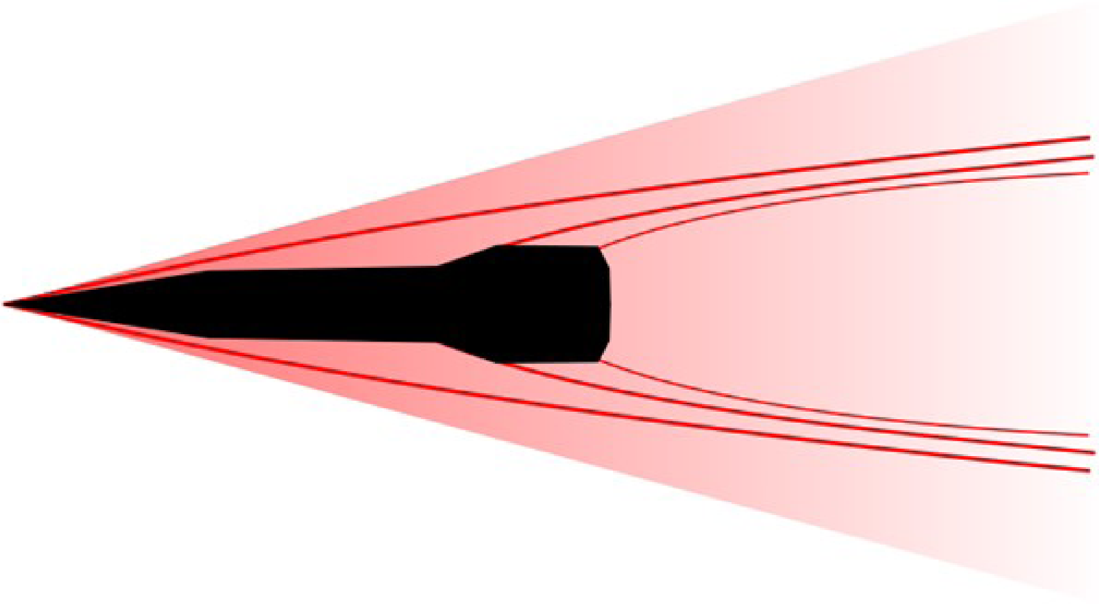
An Exploratory Analysis of the Chinese Hypersonics Research Landscape



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Key Findings

While China does not publicize its Hypersonic Vehicle (HV) development plans, some details regarding its priorities are discernible.

A 2012 book by two leading HV researchers Cai Guobiao and Xu Dajun provides a framework that informs our understanding and evaluation of Chinese HV research and development (R&D) priorities and activities. The authors, being well-versed in the layout and capabilities of the Chinese aerospace R&D ecosystem, identified 31 technologies organized into the six categories to serve as the basic framework guiding R&D activities. To assist R&D program planners in their formulation of China's HV research development strategy, they derived an HV Technology Criticality Ranking of the 31 technologies based on their assessment of the significance of these technologies for HV development and their required level of effort needed to make significant progress.

The motivations for and techniques used by Cai and Xu in developing their HV development framework and the associated technology criticality rankings are analogous to the US Air Force's Lead-Leverage-Watch model or the US Army's Lead-Collaborate-Watch model for R&D research prioritization. The motivation is to invest scarce resources in the critical technologies that will enable achievement of disruptive capabilities quickly and efficiently. The technique is to prioritize investment in critical, capability-specific enabling technologies while deprioritizing investment in technologies which, while also necessary for the disruptive capability, are obtainable by leveraging the work of others (because the technology has broad applicability and investment beyond the specific desired capability). For example, the materials category ranked lower on Cai and Xu's criticality rating because of its broad applicability beyond HV. Cai and Xu's HV development framework may be informative as to how China is implementing a lead-leverage-watch paradigm of their own in the race to develop HVs.

Quantitative analysis confirms alignment between the indicated priorities and actual Chinese Research and Development (R&D) output.

Insights yielded from qualitative analysis of Cai and Xu's work in 2012 was used as the basis for the quantitative analysis conducted in the next step. Using natural language processing (NLP) and clustering techniques resulted in 64 technology clusters which reflects actual Chinese hypersonics research activity between 2012 and 2020. Mapping actual research activity to Cai and Xu's framework is challenging due to timing, technique, and perspective. However, the quantitative analysis does confirm alignment between the indicated priorities and actual Chinese Research and Development (R&D) output. In particular, out of the 64 technology clusters identified via quantitative analysis, the top three largest (number of documents) *and* fastest growing clusters by far map to Cai and Xu's three most important technologies as shown below.

Table 1. Top Three HV Development Technologies

HV Development Framework Focus From Cai and Zu		**Quantitative Cluster Mapping**	
Cai and Xu Discussion Focus	**Criticality Rating**	**Size Ranking**	**Growth Ranking**
C2-1 Scramjet engine technology	1/31	1/64	2/64
C2-2 Combined propulsion system technology	2/31	3/64	1/64
C1-1 External design and aerodynamic force numeric simulation technology	3/31	2/64	3/64

High criticality technology clusters saw major spikes in activity in 2016

Technologies rated most critical by Cai and Xu in the Overall Technology and Propulsion Groups saw tremendous increases in research activity starting in 2016. The precise causes of this increased activity are unclear, but the growth trajectory in these areas has continued to increase year over year since 2016. Research and development programs supporting HV development are mostly classified, but the following two funding pipelines launched in the early 2000s might have contributed to the significant growth in publication output in the mid-2010s.

- HV technology R&D is rumored to be one of the undisclosed 16 national R&D megaprojects outlined in the 2006 Medium to Long-Term Plan for the Development of Science and Technology (2005-2020) (2006 MLP). It is reasonable to assume that researchers who were funded under this megaproject would have needed to publish their work prior to the 2020 deadline.
- Additionally, in December 2016, the National Natural Science Foundation of China (NSFC) announced the successful conclusion of the Key Basic Scientific Issues of Near-Space Vehicles project it had launched in 2007, after investing RMB 190 million (approximately $33 million in 2021) into a total of 173 areas related to HV technologies. NSFC has also been funding basic research on “Some Major Fundamental Issues of Aerospace Vehicles” since 2002.

Most Chinese patent filings related to HVs are filed domestically

In general, a patent that has been filed and granted in multiple international jurisdictions is likely to be a valuable and unique patent. This is due to both the challenge and expense associated with gaining international patents. While China has been active in patenting HV technology domestically, its activity internationally is extremely limited. It is possible that their quality is considered low (also suggested in anecdotal reports from Chinese scientists), though the focus on domestic applications (including weapons) may also be a factor. Additionally, patent filings have declined across the board in recent years. We suspect the cause is due to a broader crack down in China on patents that do not have a defined or immediate application. Patent filings did provide an additional data source with which to study Chinese HV activity, particularly in Group C4 Testing and Verification Technology and C6 Flight Demonstration and Validation where few journal articles were found.

Quantitative analysis largely confirms the size and membership of China’s hypersonic R&D ecosystem

The group of institutions considered to be China’s defense R&D powerhouses are well represented in the data results, both in terms of publications and patents. The ‘small core’ of legacy aerospace and defense giants such as CASC, CASIC, and AVIC are joined by vibrant programs at the Chinese Academy of Sciences and military and civilian universities such as the National University for Defense Technology, Harbin Institute of Technology, Xiamen University and connected companies. Publication and patent output of these institutions also align with their respective areas of expertise.

The next generation of Chinese HV scientists are being trained domestically

In contrast with the first generation of missile and hypersonic technology experts which included many who attended academic programs outside China and the immediately-following generation which, as a cohort, also had extensive experience abroad, China's rising generation of scientists and engineers are trained domestically and remain within China with the exception of short stints abroad. Two institutions in particular, the Harbin Institute of Technology (HIT) and National University of Defense Technology (NUDT) together appear to play an outsized role in cultivating the younger generation of hypersonic and aerospace scientists and engineers. This suggests that China has 'pockets of excellence' in missile and specifically HV R&D, which are in this case closely connected to PLA priority development areas.

Researchers from HIT, a leading institution for R&D for the PLA, publish extensively across clusters compared to researchers at other institutions, which appear to have more distinct areas of focus. This might be attributed to the fact that HIT established a hypersonic technology research center in July 2007 to comprehensively support China's hypersonic and near-space flight vehicle technological development needs.

Chinese international cooperation on hypersonic technologies appears to be limited

While China is clearly collaborating with universities and scholars abroad, with a few exceptions, the most directly relevant patent and publication activity (suggestive of overall R&D efforts) is concentrated within the Chinese domestic HV R&D ecosystem and not the result of international collaboration.

Abbreviations

AHP	Analytic Hierarchy Process
AVIC	Aviation Industry Corporation of China
BUAA	Beihang University
CAE	Chinese Academy of Sciences
CAS	Chinese Academy of Sciences
CASC	China Aerospace Science and Technology
CASIC	China Aerospace Science and Industry Corporation
CASS	Chinese Academy of Social Sciences
CAST	China Academy of Space Technology
CCP	Chinese Communist Party
CETC	China Electronics Technology Company
COMAC	Commercial Aircraft Corporation of China
CMC	Central Military Commission
EDD	Equipment Development Department
GAD	General Armament Department
HV	Hypersonic Vehicle
MCF	Military-Civilian Fusion
MIIT	Ministry of Industry and Information Technology
MOST	Ministry of Science and Technology
NASP	National Aero-Space Plane [program]
NDU	National Defense University
NSFC	National Science Foundation of China
NUAA	Nanjing University of Aeronautics and Astronautics
NUDT	National University of Defense Technology
PLA	People’s Liberation Army
PRC	People’s Republic of China
WIPO	World Intellectual Property Organization

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Introduction

1. Purpose of this Report

According to reports, China conducted tests of hypersonic glide vehicles in July and August 2021, which Chairman of the Joint Chiefs of Staff Gen. Mark Milley described as "concerning."[1] China's hypersonic weapons program has drawn significant global attention and research interests in recent years. DOD's *Annual Report to Congress on Military and Security Developments Involving the People's Republic of China* first mentioned hypersonic glide vehicles in 2015. The hypersonic glide vehicle-equipped DF-17 missile, unveiled at China's 2019 National Day Parade, further fueled speculation and interest about China's hypersonic research and development (R&D) program. Subsequent reporting indicates that units with these missiles have already been deployed. Other evidence suggests that China is engaged in a wide range of hypersonic weapons programs including wave-riders and cruise missiles.

To date, open-source English-language analysis of the subject has focused heavily on the strategic drivers and disruptive impacts of the program.[i] Other studies that looked at technical aspects focused on a small set of technologies.[ii] This report adopts a different approach, using a framework developed by Chinese scientists for prioritizing technologies for development, and then applying machine-learning-enabled analytics to analyze China's hypersonic research and development activities in those areas over time. It investigates the following research questions:

- Does the HV development framework proposed by Cai and Xu align with subsequent Chinese research activity?
- Who are the institutions, researchers, and international collaborators leading China's HV research programs?
- How has China's HV research activity evolved over time?

By adopting this approach, the goal is not only to provide an assessment of the state of hypersonic R&D for the China-analysis community, but also for the broader U.S.-scientific research community who wishes to understand China's research approach and progress in this key technology area.

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[i] See for example Zhao Tong, Conventional Challenges to Strategic Stability: Chinese Perception of Hypersonic Technology and the Security Dilemma, Carnegie Institute, July 2018. https://carnegieendowment.org/files/Conventional_Challenges_to_Strategic_Stability.pdf; Lora Saalman, "China's calculus on hypersonic glide," SIPRI, 15 August 2017. https://www.sipri.org/commentary/topical-backgrounder/2017/chinas-calculus-hypersonic-glide

[ii] See for example Peter Wood, with Roger Cliff, A Case Study of the PRC's Hypersonic Systems Development, China Aerospace Studies Institute, August 2020. https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Other-Topics/2020-08-25%20CASI_Hypersonic%20Case%20Study_WEB.pdf

2. Methodology, Definitions, and Limitations

This report combines open-source native language intelligence analysis techniques with quantitative analysis to study Chinese focus and progress in hypersonic technology development over time. Our analysis follows a three-stage process and the results are organized into the three sections of this report.

Stage 1: Establish Analytic Framework through Qualitative Analysis

The goal for this study was to go beyond traditional descriptive methods for understanding Chinese HV programs that describe the R&D ecosystem or pull together statements and descriptions of notable tests. To that end, this report based its quantitative analysis on insights gained from a 2012 book, titled *Hypersonic Vehicle Technology* [高超声速飞行器技术], which was the first book to comprehensively introduce HV technology in China.[iii] *Hypersonic Vehicle Technology* represents a rare glimpse into the R&D priorities China was pursuing as identified by Chinese HV subject matter experts (SMEs) and the framework they were using to guide their decision making process. The insight into the Chinese research and development strategy for HV gained from quanlitative analysis of the book is then used as the baseline for the subsequent quantitative analysis, the results of which are outlined in Section 1 of this report.

Stage 2: Break Down Chinese HV Research Output through Quantitative Analysis

In the second step of the process, a quantitative analysis of Chinese scientific output (publications and patents) aligned to the technology framework outlined in the book was performed. The analysis compares the book's HV development framework and technology prioritization with actual Chinese research and patent activity over time. The goal of the quantitative analysis was to use advanced natural language processing and data analytic techniques to better understand what the data shows in terms of activity and impact. The raw data for analysis consisted of peer-reviewed journal articles, conference papers, and patents representing over 300 million documents. The steps in the quantitative analysis process are as follows:

Step 1: The first step involved developing a comprehensive document corpus using both lexical and semantic techniques. The collection period was limited to January 1, 2012 – December 31, 2020. A Boolean query was developed with relevant key words, producing 3,065 "seed" documents containing these keywords. However, keyword-based or lexical queries, miss important content because the results are only as comprehensive as the keywords. Therefore, semantic search techniques were also used to identify similar documents related to the "seed" documents that did not contain terms from the set of keywords. This resulted in a corpus of 13,373 documents. Combining lexical and semantic search provided higher confidence that the data driving this study represented a comprehensive view of the HV research landscape.

Step 2: Semantic search ensures a comprehensive view of a given research landscape, but it also introduces "noise" in the data relative to the topic of interest. In general, when deciding which clusters to retain, we choose a more expansive definition to ensure capture of relevant activity, because we did not want to miss research clusters and partners with relevance to understanding China's HV activity and focus over time. Removing clusters with low pertinence to HV resulted in 64 clusters covering 11,638 total documents.

[iii] Cai Guobiao and Xu Dajun, *Hypersonic Flight Vehicle Technology* [高超声速飞行器技术] (Beijing: China Science Publishing & Media [科学出 版社], 2012), i.

Step 3: The clusters were then mapped to the book framework and activity was analyzed over time. The results of the quantitative analysis process are presented in Section 2, organized into seven subsections. Subsections 2.1 through 2.6 describe research clusters we have identified and aligned with the framework described in Section 1 and we provide breakdowns of the relevant clusters in each subsection. Section 2.7 is a standalone cluster that represents a new research direction not covered by Cai and Xu, but that we considered important and relevant.

Step 4: A supplemental patent analysis was conducted to show transition progress and provide additional data for HV technology development, particularly for areas where journal activity was sparse, such as Testing and Verification Technology [试验验证技术] and Flight Demonstration and Validation Technology [飞行演示验证技术].

Stage 3: Identifying Notable Rising Researchers and Their Collaboration Networks.

In the last stage of our analysis, we combined quantitative and qualitative analysis to identify notable rising HV researchers and their collaboration networks. The quantitative analysis was used to identify and analyze the next generation of key Chinese HV researchers. These researchers are selected out of a group of 240 researchers identified by our methodology as "rising stars" in the field of HV development. This was achieved by first narrowing the list of researchers from our data set to researchers with an initial publication date after the year 2000, then sorting the remaining authors by their first HV publication year and h-index (defined below) and retaining the top 20 authors. We then selected a group of the ten most noteworthy researchers that have clear affiliations with the PLA and China's defense industry and provide brief biographical overviews and details on their research networks.

Definitions of Key Indicators

Below is a list of indicators used throughout this report.

Hypersonic vehicle relevance (HV relevance): The percentage of documents within a document cluster that contained at least one key HV keyword (i.e. hypersonic, ramjet, scramjet, waverider) in the title or abstract. This metric indicates the degree to which a cluster was focused on hypersonic-specific research and development versus broader technical applications.

Growth: Publication and patent growth was measured by computing the change in documents per year, computed using standard linear regression. For example, a cluster growing at a rate of 7.43 added that number of documents per year on average from 2012 through 2020. A regression-based growth measure is perhaps less intuitive than a statistic like year-over-year percentage growth. However, data for patents and smaller clusters was sparse, making percentage-based growth measures difficult to calculate without distorting the data in ways that could skew interpretation. A regression-based method was a uniform and statistically viable approach.

Cluster: A collection of documents related to the same topic.

Unique invention: The patent analysis focused on identifying new and unique inventions. Patents must be filed in a particular country and, except for patents filed with the World Intellectual Property Organization (WIPO),[iv] only offer intellectual property protection in that country. Therefore, it is common for inventors to file patents in multiple countries to protect the same underlying invention. In patent terminology, a collection of patents covering the same invention is known as a "patent family." The present analysis focused on patent families, which are referred to as "unique inventions" in this report.

H-index: A statistic measuring the impact of a researcher based on the number of papers they have published and the number of times those papers have been cited in other works. H-indexes are commonly used to measure academic impact, and while they have limitations, the index is a common metric in bibliometric analysis. Typically, a researcher's h-index is computed based on their entire body of publications. For this report, we adapted h-indexes to gauge impact in the area of hypersonics by only computing it over publications included in the analysis. It is possible that a researcher identified in this report might have a high "hypersonics h-index," but a low traditional h-index.

[iv] In theory, WIPO patents offer protection in all countries that are signatories to the Patent Cooperation Treaty. However, in practice, inventors will still seek country-specific patents to ensure protection of highly valuable IP.

Limitations

It is important to note the limitations of our methodology and this report:

- The report authors lack specific subject matter expertise over the broad areas of science covered by this report. The cluster mapping process therefore includes a margin of error given the lack of in-depth scientific domain knowledge.
- The report was prepared without classified information. Given the subject matter, this was likely a significant limitation.
- The qualitative analysis is based on a book describing the views of the Chinese authors in 2012. While the authors are believed to be authoritative SMEs in the Chinese HV development ecosystem, their viewpoints are by nature subjective and timebound. The quantitative analysis on the other hand, is based on actual data over the subsequent nine years that was analyzed using NLP and clustering techniques. A perfect crossmatch between the 31 critical technologies prioritized by Cai and Xu with the 64 research clusters identified by the quantitative analysis was not expected.
- To mitigate the limitations of the analytic approach and team:
- Detailed data is provided in the report and appendix sufficient to enable technical experts to make their own assessments.
- Proposed follow-ups include involving technical experts and classified data in any follow-on analysis.

3. Organization of the Report

Our analysis follows a three-stage process, with the results of analysis from each stage organized into the three sections of this report.

Section 1 provides an overview of the analytic framework presented in a Chinese textbook on HV technology development, which gives us insight into the Chinese research and development strategy for HV and serves as the baseline for the subsequent quantitative analysis.

Section 2 presents the results of our quantitative analysis of Chinese scientific output aligned to development strategy outlined in the book. The results are organized into seven subsections. Sections 2.1 to Section 2.6 include research clusters we have identified and aligned with the qualitative analysis from Section 1. Section 2.7 is a standalone cluster representing a new research direction not mentioned in the book.

Section 3 identifies and profiles ten notable rising HV researchers and offers insights into their collaboration networks.

The **Appendixes** provide additional detail on interesting research and patents uncovered by data analytics.

Section 1: Qualitative Analysis of Hypersonic Vehicle Technology (2012)

1.1 Analytic Framework

The basis for qualitative analysis in this paper is an analytic framework presented in a Chinese textbook on HV technology development. The 2012 book, titled *Hypersonic Vehicle Technology* [高超声速飞行器技术], was the first book to comprehensively introduce HV technology in China[v] and represents a rare glimpse into the decision making and prioritization in the eyes of the SMEs behind Chinese Hypersonic Vehicle R&D. The book is chosen as the framework based on the following grounds:

- Its authors, Cai Guobiao [蔡国飙] and Xu Dajun [徐大军], are two Beihang University (BUAA)[vi] [北京航空航天大学] professors with extensive ties to China's defense research community and the People's Liberation Army (PLA).[vii] In particular, the lead author of the book, Cai Guobiao, has been identified as a prominent HV researcher and recipient of multiple civilian and defense science & technology (S&T) awards.
- Beihang has been a major player in hypersonics development, receiving 18 National Science Foundation of China (NSFC) grants between 2000 and 2013 for research programs designed to advance basic research in hypersonic flow technologies.[2]
- Both Cai and Xu are affiliated with Beihang's School of Astronautics [宇航学院], a powerhouse for the research and development of rockets, missiles, rocket engines, and other related technologies since the 1950s.[3] Among its alumni are former PLA Second Artillery (now Rocket Force) and PLA Air Force commanders, Chinese Academy of Sciences (CAS) and Chinese Academy of Sciences (CAE) Academicians, as well as chairs and general managers of China's largest state-owned aerospace defense corporations. The School of Astronautics runs several laboratories and research centers set up jointly with research academies from China's two main aerospace contractors, China Aerospace Science and Technology Corporation (CASC) and China Aerospace Science and Industry Corporation (CASIC).[4] Cai previously served as the managing Deputy Director of the school and as of June 2021 serves as the Director of the School's Aerospace Flight Vehicle Technology Research Institute [空天飞行器技术研究所], an organization created to work on BUAA's cross-discipline major research projects [学校重大项目跨学院研究所].[5]

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[v] Cai Guobiao and Xu Dajun, Hypersonic Flight Vehicle Technology [高超声速飞行器技术] (Beijing: China Science Publishing & Media [科学出版社], 2012), i.

[vi] Beihang University was previously known as Beijing University of Aeronautics and Astronautics (BUAA).

[vii] The authors' biographies are included in Appendix 1.

- According to Cai and Xu, their work received a tremendous amount of attention and support from numerous experts, including leaders and researchers from the then PLA General Armament Department's (GAD) Science and Technology Commission,[viii] the then-PLA GAD Electronic Information Infrastructure Department 解放军电子信息基础部],[ix] CASC's First Academy,[x] CASIC's Third Academy,[xi] as well as late Academicians Zhuang Fenggan [庄逢甘], a noted expert in the field of aerodynamics, and Liu Xingzhou [刘兴洲], a noted expert on cruise missile propulsion.[6]

Taken together, their positions within the Chinese HV development ecosystem, association with a prestigious program and their book's reception within the Chinese defense R&D community are strong indications of the authoritativeness of their views regarding hypersonic development.

Cai and Xu note that a great number of Chinese universities and government research institutes have launched research programs on HV-related technology in recent years and have made significant progress. At the same time, they acknowledge the significant technical hurdles posed by HV R&D and note that certain features of HV development in particular, such as integrated design of the fuselage and propulsion system and the requirement for high-level multidisciplinary integration, make research methods and the technological development pathways different from the traditional flight vehicle development process. Seeing no domestic or international publication that systematically introduced HV technology at a general level to a broad academic audience, the authors set about writing a primer that could give Chinese HV researchers and engineers a comprehensive, high-level, and interdisciplinary understanding of HV technological systems. The book discusses the main research areas and methods for key HV technologies and summarizes other countries' R&D programs and major research achievements in HV technology.

[viii] Now the Science and Technology Commission under the Central Military Commission (CMC).

[ix] Now likely the CMC Equipment Development Department's Information Systems Bureau [中央军委装备发展部信息系统局].

[x] Also known as the China Academy of Launch Vehicle Technology (CALT) [中国运载火箭技术研究院].

[xi] Also known as China Haiying Electro-Mechanical Technology Academy [中国海鹰机电技术研究院], AKA CHETA, HiWING or CASIC Aerodynamic Missile Technology Research Academy [航天科工飞航技术研究院]. The Third Academy conducts general research, design, development, and production of anti-ship and land-attack cruise missiles.

1.2 Six Major Categories of HV Technology

While the book cites a large amount of foreign and domestic academic research material, the authors offered some information, assessments, and insights that appear to be original. Notably, the authors divided the key technologies involved in the development of hypersonic flight vehicles into six major technology categories and listed the key technologies under each category (**Table 2**). According to the authors, this classification was based on both the division of academic disciplines and the existing structure of the Chinese aerospace industry.

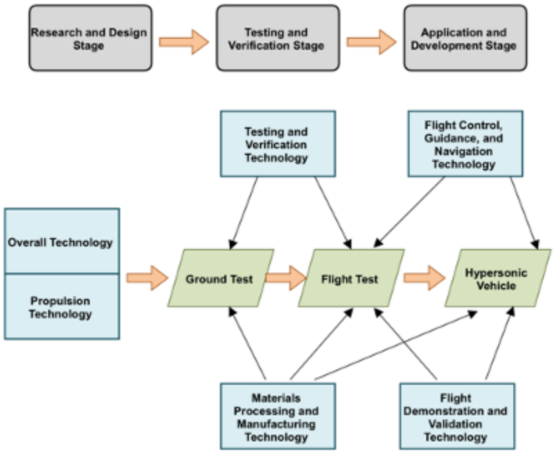
Table 2. Six Major Categories of HV Technology (via Cai and Xu)

Code	Name	Code	Name
C1	Overall Integrated Design Technology [总体技术]	C1-1	External design and aerodynamic force numeric simulation technology [外形设计与气动力数值模拟技术]
		C1-2	Integrated design technology [一体化设计技术]
		C1-3	Interdisciplinary design optimization technology [多学科设计优化技术]
		C1-4	Aerodynamic heating numeric simulation technology [气动热数值模拟技术]
		C1-5	Structural design thermal protection and heat management technology [结构设计热防护与热管理技术]
		C1-6	Flight emulation technology [飞行仿真技术]
C2	Propulsion Technology [推进技术]	C2-1	Scramjet engine technology [超燃冲压发动机技术]
		C2-2	Combined propulsion system technology [组合推进系统技术]
		C2-3	Propulsion system control technology [推进系统控制技术]
		C2-4	Hypersonic propulsion engine thermal structure and cooling technology [高超推进发动机热结构与冷却技术]
		C2-5	Endothermic hydrocarbon fuel technology [吸热型碳氢燃料技术]
C3	Materials / Processing / Manufacturing Technology [材料/工艺/制造艺术]	C3-1	Heat-resistant and thermal insulation materials [防热与隔热材料]
		C3-2	Heat-resistant coating materials [防热涂层材料]
		C3-3	Light(weight) high-strength materials [轻质高强度材料]
		C3-4	Atypical structural design and shaping technology [异型结构设计与成型技术]
		C3-5	Component joining, welding and sealing technology [部件连接、焊接与密封技术]
C4	Testing and Verification Technology [试验验证技术]	C4-1	Direct-connected super-combustion chamber testing technology [直连式超燃燃烧室试验技术]
		C4-2	Scramjet engine free jet testing technology [超燃冲压发动机自由射流试验技术]
		C4-3	Combined propulsion systems testing technology [组合推进系统试验技术]
		C4-4	Hypersonic wind tunnel technology [高超声速风洞技术]
		C4-5	Hypersonic aircraft aerodynamic force testing technology [高超声速飞行器气动力试验技术]
		C4-6	Hypersonic vehicle aerodynamic heating testing technology [高超声速飞行器气动热试验技术]
		C4-7	Heat-resistant structural materials thermal environment simulation and testing technology [防热结构材料热环境模拟与试验技术]

C5	Flight Navigation, Guidance, and Control Technology [飞行导航制导与控制技术]	C5-1	Hypersonic vehicle aerodynamics/propulsion integrated control technology [高超声速飞行器气动/推进一体化控制技术]
		C5-2	Hypersonic cruise vehicle navigation and control technology [高超声速巡航飞行器导航与控制技术]
		C5-3	Hypersonic remote strike weapon precision guidance and control technology [高超声速远程打击武器精确制导与控制技术]
C6	Flight Demonstration and Validation Technology [飞行演示验证技术]	C6-1	Flight testing risk assessment (technology) [飞行试验风险评估技术]
		C6-2	Aerial launch technology [空中发射技术]
		C6-3	Ground launch technology [地面发射技术]
		C6-4	Hypersonic separation technology [高超声速分离技术]
		C6-5	Flight testing telemetry (technology) [飞行试验遥测技术]

The way these six technical categories fit into the three stages of the R&D process is illustrated in **Figure 1**. According to Cai and Xu, the overriding goal during the research and design stage is to achieve breakthroughs in fundamental principles and theories for technologies in the C1 and C2 categories. They commented that both areas represented unprecedented challenges due to their uniqueness that separated them from traditional flight vehicle design and R&D. The testing and verification stage, which focuses on testing the feasibility of designs, primarily involves technologies in C3 and C4. Breakthroughs in the majority of critical technologies should have been achieved by the time a project enters the application and development stage, and C3 and C5 technologies begin to play bigger roles. At the same time, some problems may be encountered that were not previously considered at the design and research stage, and it is necessary to carry out additional theoretical and principle-based research work.

Figure 1. Mapping of Six Technical Categories to R&D Phases



Cai and Xu argued that the classification contributes to a comprehensive understanding of the necessary technologies to achieve the R&D end goal, which would in turn facilitate more efficient R&D planning and help prevent uneven development from causing delays to the whole program. They note that due to the multi-disciplinary nature of HV R&D, many countries have established national R&D programs, such as the United States' National Aero-Space Plane (NASP) Program and Germany's Sanger Program, to optimize and coordinate R&D activities at the state level. The authors reasoned that at the heart of a state-level R&D program there is a well-researched development strategy, which is itself a complicated and systematic task that cannot rely solely on the subjective experience and opinions of the policy makers. The authors recommended introducing scientific methods such as quantitative analysis, supplemented by empirical judgment and intuitive thinking, to assist the decision-making process.[xii]

To that end, the authors adopted a complex-decision-making framework developed by University of Pittsburgh Professor Thomas L. Saaty in the 1970s, known as the Analytic Hierarchy Process (AHP), to rank the "criticality" [关键度] of the 31 HV key technologies (**Table 2**)[xiv].

[xii] The authors seem to suggest a degree of resistance from the Chinese S&T policy and research planning bodies which were unfamiliar with use of quantitative analysis to set research priorities. They also indicated that China has yet to develop its own technology readiness level (TRL) measurement system for hypersonic technologies, but argued that the criticality ranking list and the TRL system—two tools for setting priorities—can strongly support the formulation of (China's) hypersonic vehicle development strategy and the design of HV research programs

AHP[xiii] is a structured decision analysis method that uses quantitative ratings to measure the value, or "criticality," of a set of alternatives against multiple criteria. Criteria and alternatives are organized in a hierarchy, which allows for complex decision landscapes with multiple levels of nested criteria and alternatives. A full explanation of AHP is beyond the scope of this paper, but interested readers may consult Saaty's 1982 introductory book.[xv]

To frame their AHP model, the authors constructed a five-layer hierarchical framework consisting of:

1. An overall goal (HV technology development)
2. Two groups of Objectives
    1. Objectives Layer: a group of objectives from a broad perspective for reaching the goal (i.e., the six major categories of HV technologies)
    2. Alternatives Layer: a group of alternatives (subset of objectives; i.e., the technologies identified under each of the six categories)
3. Two sets of Criteria
    1. Criteria Layer 1:
        - B1: technology categories unique to HV [高超声速飞行器所特有的技术类别]
        - B2: technology categories that intersect with other technical fields (the greater the intersection, the lesser the importance) ([其他技术领域有交集的技术类别(交集越大，越不重要)]
        - B3: categories consisting of starting point (entry-level) HV technologies [高超声速飞行器起点的技术类别]
    2. Criteria Layer 2:
        - BB1: Technologies unique to HV development ([超声速飞行器所特有的技术]
        - BB2: Highly difficult technologies indispensable to HV development [高超声速飞行器发展所必需的，且具有较大的难度]
        - BB3: HV entry-point technology [高超声速飞行器技术发展的切入点技术]

A core aspect of AHP is the collection of pairwise comparisons of criteria and alternatives from decision stakeholders. Within each layer of decision criteria, stakeholders rate the relative importance of the criteria for the overall goal of the decision[vxi]. In addition, stakeholders rate their preference for each alternative relative to the criteria. AHP typically uses a 9-point rating scale for comparing two items that gauges whether one item is more preferred than the other, with the midpoint indicating no preference. Rating can either be collected from stakeholders individually and averaged, or developed via a consensus-based approach such as the Delphi method.

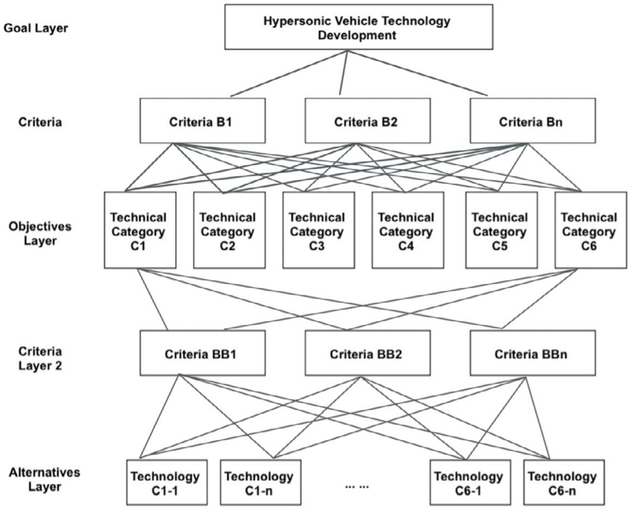
[xiii] It is worth noting that it is the essence of the AHP that human judgments, and not just the underlying information, are used in performing the evaluations. In other words, by adopting the AHP framework, the authors indicated their expert judgments about one HV technology's relative importance against another through pairwise comparisons.

[xiv] The process by which the authors derived the priority scale of HV technology is included in Appendix 2.

[xv] Saaty, Thomas L. Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in a Complex World (1982). Belmont, California: Wadsworth.

[xvi] In an AHP with multiple levels of criteria, stakeholders rate the importance of criteria at one level of the hierarchy relative to their "parent" criterion at the next-highest level of the hierarchy.

Figure 2. Cai and Xu's Analytical Hierarchical Process



Cai and Xu did not provide much detail on their stakeholder population or data collection methods. However, they did report the outcomes of the analysis in significant detail. For example, the authors derived rankings of the six major categories of HV technologies. **Table 3** provides the ranking data from the book, along with the score for each major technology category on each of the three main decision criteria. One notable insight is that the stakeholders Cai and Xu engaged with viewed criterion B3 (whether a category is an "entry-level" or foundational technology domain) as the most important driver of overall category criticality (i.e., how valuable the category is for developing the Chinese hypersonics ecosystem). This may reflect a perception that China had gaps in the key enabling technologies for hypersonics at the time this analysis was conducted in 2012. Looking at the criticality ratings for the technologies, category C2 (propulsion technology) emerged at the most valuable overall, followed by C1 (overall technology) and C4 (testing and verification technology).

Table 3. HV Technology Pairwise Comparisons

Criteria (importance)				
Technology Category	B1 (0.2789)	B2 (0.0719)	B3 (0.6491)	Overall Criticality for Category
C1	0.1684	0.2294	0.2805	0.2455
C2	0.3232	0.2914	0.4279	0.3888
C3	0.0488	0.0323	0.0488	0.0476
C4	0.2241	0.2169	0.1466	0.1733
C5	0.0488	0.0493	0.0474	0.0479
C6	0.1866	0.1806	0.0488	0.0967

1.3 Criticality Ranking

Cai and Xu also reported criticality ratings for the component technologies within each of their six categories. Their results are replicated in **Table 4**. As defined in the book, "intensity of category" is the criticality of the technology category, corresponding to the data provided above in **Table 3**. "Intensity of technology within category" is the relative value of each technology compared with other technologies in the same category. "Criticality" is the overall value of each individual technology across the entire set of 31 technologies; in other words, this value gives the overall order of importance assigned by the stakeholders. Scramjet engine technology was the most critical technology by a wide margin, which was consistent with the stakeholders emphasis on fundamental enabling technologies. Another metric reported by Cai and Xu was "value assignment," which appears to be an overall categorical rating of the technologies. The authors do not provide a detailed description of how value assignment was established, but it appears to be driven by a metric they call the "stochastic consistency index." The definition of this metric is not provided, but it may reflect the consistency of ratings across stakeholders.

Table 4. Criticality Ranking

ID	Intensity Of Category	Intensity of Technology within Category	Criticality	Name of Technology	Value Assignment
C2-1	0.3888	0.4296	0.1670	Scramjet engine technology [超燃冲压发动机技术]	9
C2-2	0.3888	0.2205	0.0857	Combined propulsion system technology [组合推进系统技术]	5
C1-1	0.2455	0.3109	0.0763	External design and aerodynamic force numeric simulation technology [外形设计与气动力数值模拟技术]	5
C2-4	0.3888	0.1576	0.0613	Hypersonic propulsion engine thermal structure and cooling technology [高超推进发动机热结构与冷却技术]	4
C1-2	0.2455	0.2136	0.0525	Integrated design technology [一体化设计技术]	3
C4-1	0.1733	0.2952	0.0511	Direct-connected super-combustion chamber testing technology [直连式超燃燃烧室试验技术]	3
C2-3	0.3888	0.1301	0.0506	Propulsion system control technology [推进系统控制技术]	3
C6-4	0.0967	0.5008	0.0484	Hypersonic separation technology [高超声速分离技术]	3
C1-4	0.2455	0.1877	0.0461	Aerodynamic heating numeric simulation technology [气动热数值模拟技术]	3
C4-2	0.1733	0.2093	0.0363	Scramjet engine free jet testing technology [超燃冲压发动机自由射流试验技术]	3
C1-5	0.2455	0.1444	0.0355	Structural design thermal protection and heat management technology [结构设计热防护与热管理技术]	3
C5-1	0.0479	0.7147	0.0342	Hypersonic flight vehicle aerodynamics/propulsion integrated control technology [高超声速飞行器气动/推进一体化控制技术]	2

ID	Intensity Of Category	Intensity of Technology within Category	Criticality	Name of Technology	Value Assignment
C1-3	0.2455	0.1013	0.0249	Interdisciplinary design optimization technology [多学科设计优化技术]	2
C2-5	0.3888	0.0621	0.0242	Endothermic hydrocarbon fuel technology [吸热型碳氢燃料技术]	2
C4-5	0.1733	0.1251	0.0217	Hypersonic aircraft aerodynamic testing technology [高超声速飞行器气动力试验技术]	2
C4-3	0.1733	0.1141	0.0198	Combined propulsion systems testing technology [组合推进系统试验技术]	2
C4-6	0.1733	0.1139	0.0197	Hypersonic vehicle aerodynamic heating testing technology [高超声速飞行器气动热试验技术]	2
C4-4	0.1733	0.1003	0.0174	Hypersonic wind tunnel technology [高超声速风洞技术]	2
C3-1	0.0476	0.3431	0.0164	Heat-resistant and thermal insulation materials (防热与隔热材料)	2
C6-5	0.0967	0.1673	0.0162	Flight testing telemetry technology [飞行试验遥测技术]	2
C6-1	0.0967	0.1377	0.0133	Flight testing risk assessment technology [飞行试验风险评估技术]	1
C3-2	0.0476	0.2285	0.0109	Heat-resistant coating materials [防热涂层材料)	1
C1-6	0.2455	0.0419	0.0103	Flight emulation technology [飞行仿真技术]	1
C6-2	0.0967	0.1039	0.0100	Aerial launch technology [空中发射技术]	1
C5-2	0.0479	0.2024	0.0097	Hypersonic cruise vehicle navigation and control technology [高超声速巡航飞行器导航与控制技术]	1
C3-5	0.0476	0.1962	0.0093	Component joining, welding and sealing technology [部件连接、焊接与密封技术]	1
C6-3	0.0967	0.0900	0.0087	Ground launch technology [地面发射技术]	1
C4-7	0.1733	0.0419	0.0073	Heat-resistant structural materials thermal environment simulation and testing technology [防热结构材料热环境模拟与试验技术]	1
C3-3	0.0476	0.1462	0.0070	Light(weight) high-strength materials [轻质高强度材料]	1
C3-4	0.0476	0.0857	0.0041	Atypical structural design and shaping technology [异型结构设计与成型技术]	1
C5-3	0.0479	0.0827	0.0040	Hypersonic remote strike weapon precision guidance and control technology [高超声速远程打击武器精确制导与控制技术]	1

Cai and Xu are strong advocates for using quantitative analysis to formulate technology development strategies and research plans. The criticality ranking provides a comprehensive picture of the technical requirements necessary to achieve the final development goal, and to avoid uneven technological development and delays to the development schedule. For example, they note, the “hypersonic boundary layer separation technology” is a C6 technology required during the flight demonstration and validation stage, but this specific technology ranked high (#6) in terms of its criticality, serving as a reminder to R&D program designers and funding agencies to prioritize its research and development.

Section 2: Quantitative Analysis of Scientific Output Aligned to Cai and Xu's Framework

Section 1 provided Cai and Xu's strategic framework for developing HV technologies. In Section 2, quantitative techniques are used to assess the degree of agreement between the HV development framework Cai and Xu proposed and the actual research and patent activity observable in open sources. If there is strong agreement between Cai and Xu and the data, the book's authority would be supported and may provide insights into Chinese strategies for obtaining disruptive technologies and progress on HV. It also explores the question of if the data indicates changes in Chinese HV development priorities between 2012 and 2020. More generally, what HV research is China focused on now, who is leading their efforts, and who in the international community is assisting? The quantitative analysis began with a hierarchical clustering solution of the corpus of documents derived through the lexical and semantic techniques described previously. **Table 5** shows the mapping between Cai and Xu's 31 technologies and the 64 research clusters found through quantitative analysis.

Table 5. Qualitative and Quantitative Alignment within Cai & Xu's Hypersonic Framework

Book Group	Book Ranking	Book Tech	Quantitative Clusters	Quantitative Documents
C1 - Overall Technology	0.245	6	23	3774
C2 - Propulsion Technology	0.388	5	7	1541
C3 - Materials/Processing/Manufacturing	0.047	5	10	1803
C4 - Testing and Verification Technology	0.173	7	1	72
C5 - Flight Navigation, Guidance, and Control	0.047	3	22	4448
C6 - Flight Demonstration and Validation	0.096	5	0	0
C7 – Hypersonic target detection	N/A	N/A	1	111

The quantitative analysis confirms alignment between the indicated priorities and actual Chinese R&D output. While Cai and Xu identified 31 technologies, in their book they focused on the five specific technologies shown in **Table 6**. It is therefore notable that the top three largest and fastest growing quantitative clusters map to Cai and Xu's most important technologies as shown in the table below.

Table 6. Technologies Book Discussion

HV Development Framework Focus From Cai and Xu		Quantitative Cluster Mapping	
Cai and Xu Discussion Focus	Criticality Rating	Size Ranking	Growth Ranking
C2-1 Scramjet engine technology [超燃冲压发动机技术]	1/31	1/64	2/64
C2-2 Combined propulsion system technology [组合推进系统技]	2/31	3/64	1/64
C1-1 External design and aerodynamic force numeric simulation technology [外形设计与气动力数值模拟技术]	3/31	2/64	3/64
C1-2 Integrated design technology [一体化设计技术]	5/31	N/A	N/A
C4-4: Hypersonic wind tunnel technology [高超声速风洞技术]	18/31	58/64	53/64

As noted earlier, a patent analysis was also conducted. The purpose of the analysis was to provide an additional lens through which to view Chinese progress and focus areas in HV development. Whereas research activity over time is an indicator of focus, patents can provide an indicator of progress. Patents are indicative of more advanced development activities and potential commercial applications. The patent analysis provided several additional data points, including the following:

1. Patent activity was highest in Cai and Xu's highest priority groups, C1 and C2, as shown in **Table 7**.

2. Whereas the research analysis provided little information pertinent to C4 and C6, the patent analysis did provide some data on Chinese research activities in these Groups.

3. China is not patenting its HV technologies internationally, which may be due to low quality. Chinese patent activity has also been declining in recent years. This may be related to the recent general crack down by the Chinese Communist Party (CCP) on low quality patents, particularly since the research activity in key HV technologies has been rapidly increasing at the same time.

Table 7. China HV Technologies

Domain	Unique Inventions	Inventions filed in China	Inventions granted in China	Inventions filed outside China	Inventions granted outside China
C1 - Overall Technology	276	276	151	3	0
C2 - Propulsion Technology	316	316	180	2	0
C3 - Materials/ Processing/ Manufacturing	120	120	50	2	1
C4 - Testing and Verification Technology	167	167	101	0	0
C5 - Flight Navigation, Guidance, and Control	127	127	70	0	0
C6 - Flight Demonstration and Validation	19	19	7	0	0
C7 – Hypersonic target detection	20	20	13	0	0

The subsequent sections provide a deeper dive into each of the Groups and are organized as follows:

1. Cai and Xu's description of the category including component technologies and their criticality rankings.

2. Group level quantitative analysis showing research and patent activity over time.

3. A detailed quantitative analysis of two clusters from each Group (when available) which were selected based on their growth rates, relevance, size, and relationship to Cai and Xu's critical technologies.

1.1 Overall Technology Group

Overview 2.1

Overall Technology is the broadest of the six technology Groups. Cai and Xu gave it the second highest Group ranking after propulsion overall, and it also has high B2 and B3 scores (intersection with other technical fields and starting point technology). Cai and Xu's description of the Overall Technology Group is provided in the box below.

C1 - Overall Technology [总体技术]

Technologies in the C1 category guide the entire R&D process from research and design to prototyping, and involve design methods, design optimization, and other related foundational technologies. Due to the uniqueness of hypersonic vehicles, aerodynamic heat, thermal protwection systems, and thermal management technologies should all be considered in the conceptual design and preliminary design stage. Additionally, the integrated design concept required by hypersonic aircraft is also a revolutionary innovation and development that sets it apart from traditional aircraft design, necessitating a need for multidisciplinary design and optimization.

Cai and Xu, 32.

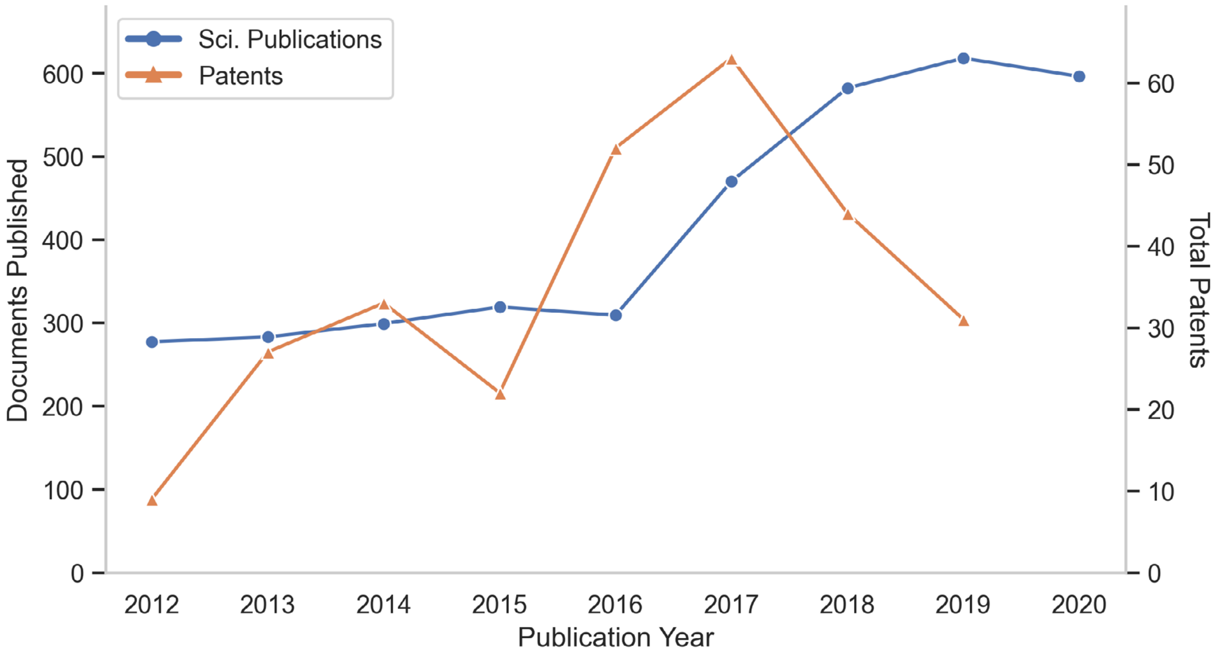
Table 8. Cai and Xu's Overall Technology Ratings

	Name of Technology	Value Assignment
C1-1	External design and aerodynamic force numeric simulation technology [外形设计与气动力数值模拟技术]	5
C1-2	Integrated design technology [一体化设计技术]	3
C1-4	Aerodynamic heating numeric simulation technology [气动热数值模拟技术]	3
C1-5	Structural design thermal protection and heat management technology [结构设计热防护与热管理技术]	3
C1-3	Interdisciplinary design optimization technology [多学科设计优化技术]	2
C1-6	Flight emulation technology [飞行仿真技术]	1

The quantitative analysis mapped 23 clusters containing 3,774 documents to the Overall Technology Group. A deeper analysis is provided on the Supersonic Aerodynamics/Flow and Aerodynamic (s/HS) Boundary Layers Clusters. These clusters were selected for drill down due to their combination of activity, growth, and HV relevance. They are also relevant to Cai and Xu's C1-1 external design and aerodynamic force numeric simulation technology which had one of the highest overall HV value assignments.

Figure 3 below shows research and patent activity over time in the Overall Technology Group. A significant inflection point occurred in 2016. Unconfirmed reports of a high tempo of hypersonic-vehicle-equipped missile tests in 2014 and 2015 and a reported breakthrough in regenerative cooling scramjets in 2015 may be indicators of progress influencing this inflection point, but there is insufficient public data to confirm it.

Figure 3. Overall Technology Research and Patent Activity



Appendix 2: Patent Analysis for Technology Group provides a sample of patents identified from this Group.

The quantitative analysis also revealed a particularly active and impactful international collaboration network in this cluster. Their research focus is supersonic aerodynamics and flows. While there were several other interesting international collaborations in this and other Groups, this one stood out due to the level of activity, impact, and the subject matter. Additional details on this collaboration are provided in **Appendix 3:** International Collaboration Supersonic: aerodynamics and flows.

2.1.2 Supersonic Aerodynamics and Flows Cluster

Documents within this cluster present studies on supersonic flows or supersonic aerodynamics. Aerodynamics are vital to all forms of flight, but supersonic flight poses unique challenges. Experimental studies in this Group focused on the characterization and manipulation of supersonic flow. Numerous numerical studies aiming to accurately predict supersonic flow behavior or supersonic aerodynamics were also present within this Group. Table 9 shows representative articles from this cluster that had high HV relevance.

Table 9. Representative Articles – Aerodynamics and Flows

Relevant Articles
Li Z, Li Z, Manh T, Gerdroodbary M, Nam N, Moradi R, Babazadeh H (2020). The effect of sinusoidal wall on hydrogen jet mixing rate considering supersonic flow. Energy, 193, 116801.
Li Z, Li Z, Manh T, Gerdroodbary M, Nam N, Moradi R, Babazadeh H (2020). The influence of the wedge shock generator on the vortex structure within the trapezoidal cavity at supersonic flow. Aerospace Science and Technology, 98, 105695.
Li Y, Gerdroodbary M, Moradi R, Babazadeh H (2020). The influence of the sinusoidal shock generator on the mixing rate of multi hydrogen jets at supersonic flow. Aerospace Science and Technology, 96, 105579.
Huang W, Du Z, Yan L, Zhixun X (2019). Supersonic mixing in airbreathing propulsion systems for hypersonic flights. Progress in Aerospace Sciences, 109, 100545.
Li L, Huang W, Yan L, Du Z, Fang M (2019). Numerical investigation and optimization on the micro-ramp vortex generator within scramjet combustors with the transverse hydrogen jet. Aerospace Science and Technology, 84, 570-584.
Huang W (2016). Transverse jet in supersonic crossflows. Aerospace Science and Technology, 50 (50), 183-195.
Huang W (2018). Mixing enhancement strategies and their mechanisms in supersonic flows: A brief review. Acta Astronautica, 145, 492-500.
Ye K, Ye Z, Li C, Wu J (2019). Effects of the aerothermoelastic deformation on the performance of the three-dimensional hypersonic inlet. Aerospace Science and Technology, 84, 747-762.
Zhang B, Liu H, Yan B (2019). Velocity behavior downstream of perforated plates with large blockage ratio for unstable and stable detonations. Aerospace Science and Technology, 86, 236-243.
Li L, Huang W, Yan L (2017). Mixing augmentation induced by a vortex generator located upstream of the transverse gaseous jet in supersonic flows. Aerospace Science and Technology, 68, 77-89.

There were 516 documents in this cluster with Chinese authors or co-authors published between 2012 and 2020. The following figures and tables provide an overview of Chinese research activity in the supersonic aerodynamics and flows cluster.

Figure 4. Growth in Chinese Research (2012 through 2020) – Aerodynamics and Flows

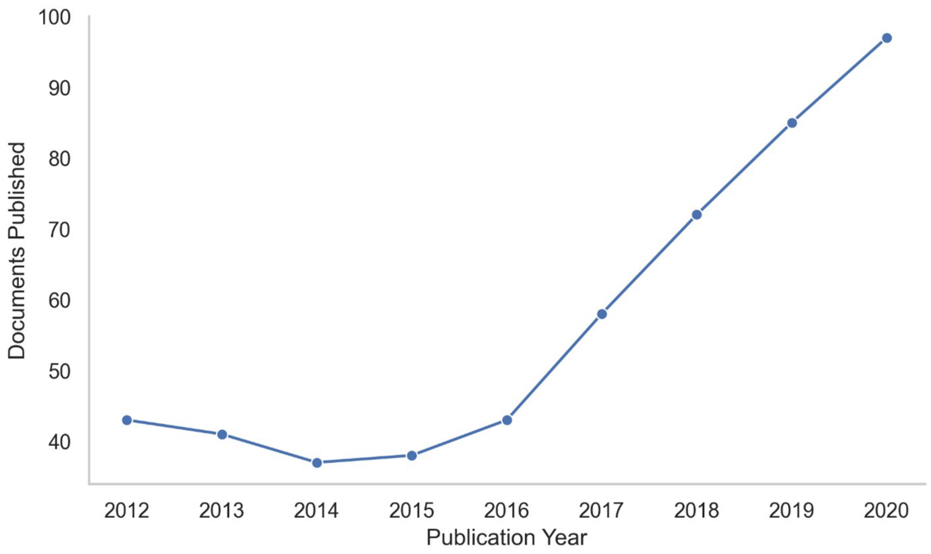


Table 10. Top Researchers – Aerodynamics and Flows

Name	Affiliation	Publication Count	Median Citations	H-Index
Huang Wei	NUDT	31	24	19
Yan Li	NUDT	21	26	13
Wang Zhenguo	NUDT	16	10	9
Sun Mingbo	NUDT	16	8	8
Liu Jun	NUDT	9	24	7

Table 11. Top Research Hubs – Aerodynamics and Flows

Name	Publication Count	Median Citations	H-Index
NUDT	133	4	21
Nanjing University of Aeronautics and Astronautics (NUAA)	60	2	10
Northwestern Polytechnical University (NWPU)	41	2	10
Beihang University	39	3	7
Tsinghua University	27	4	8

vxxviii China's National University of Defense Technology (NUDT) is the PLA's top scientific research institution.

Figure 5 Chinese International Collaborative Intensity – Aerodynamics and Flows

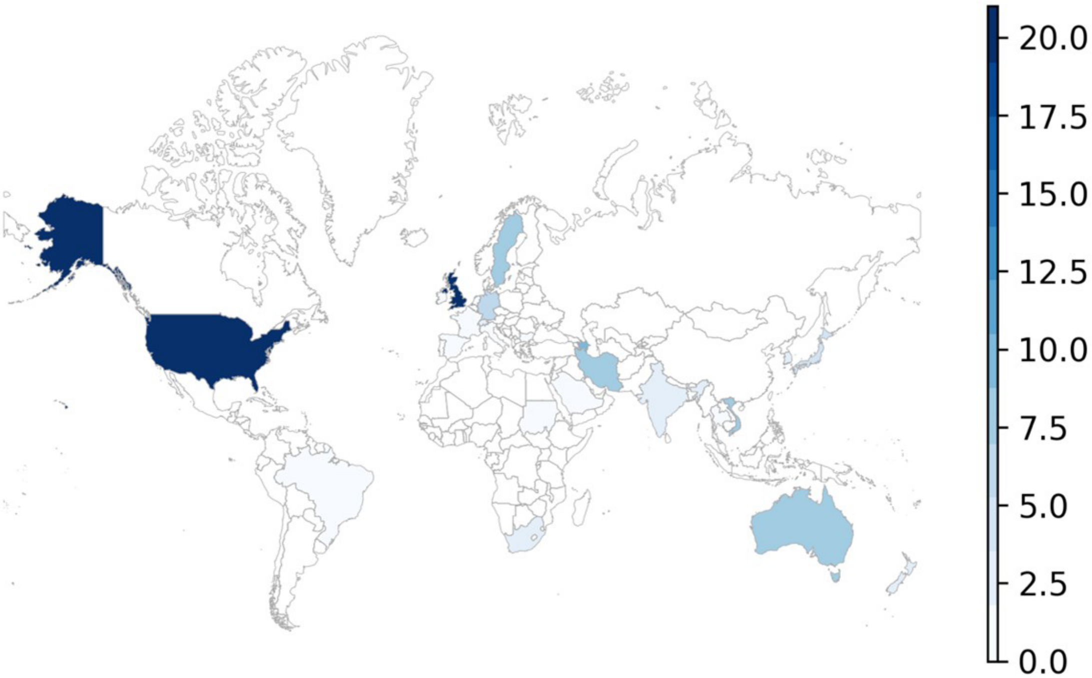


Table 12. Top Five International Collaborators – Aerodynamics and Flows

Name	Country	Publication Count	Median Citations
Khazar University	Azerbaijan	10	16
Ton Duc Thang University	Vietnam	8	13
Babol Noshirvani University of Technology	Iran	7	19
University of Wollongong	Australia	6	5
University of Southampton	United Kingdom	5	15

2.1.3 Supersonic and Hypersonic Boundary Layer Cluster

This cluster is focused on supersonic and hypersonic boundary layers. Vehicles that travel faster than the speed of sound generate a significant temperature gradient across the high viscosity region next to the surface interfacing with the supersonic flow and the low viscosity region further away from this surface. Effective management of this boundary is vital to efficient hypersonic flight. Studies within this Group approach this problem both experimentally and numerically. Table 13 shows representative articles from this cluster that had high HV relevance.

Table 13. Relevant Articles – Boundary Layers

Relevant Articles
Lee C, Chen S (2019). Recent progress in the study of transition in the hypersonic boundary layer. National Science Review, 6 (1), 155-170.
Huang W, Yan L (2016). Numerical investigation on the ram–scram transition mechanism in a strut-based dual-mode scramjet combustor. International Journal of Hydrogen Energy, 41 (8), 4799-4807.
Zhu Y, Chen X, Wu J, Chen S, Lee C, Gad-el-Hak M (2018). Aerodynamic heating in transitional hypersonic boundary layers: Role of second-mode instability. Physics of Fluids, 30 (1), 011701.
Shi L, Zhao G, Yang Y, Qin F, Wei X, He G (2020). Experimental study on ejector-to-ramjet mode transition in a divergent kerosene-fueled RBCC combustor with low total temperature inflow. Aerospace Science and Technology, 99, 105734.
Shen W, Huang Y, You Y, Yi L (2020). Characteristics of reaction zone in a dual-mode scramjet combustor during mode transitions. Aerospace Science and Technology, 99, 105779.
Huang W, Yan L, Tan J (2014). Survey on the mode transition technique in combined cycle propulsion systems. Aerospace Science and Technology, 39, 685-691.
Ma K, Li J, Qiang L, Liu Y (2020). Experimental study on evolution characteristics of plane subsonic-supersonic shear layer. Aerospace Science and Technology, 100, 105791.
Wang T, Li G, Yang Y, Wang Z, Cai Z, Sun M (2020). Combustion modes periodical transition in a hydrogen-fueled scramjet combustor with rear-wall-expansion cavity flameholder. International Journal of Hydrogen Energy, 45 (4), 3209-3215.
Chen X, Huang G, Lee C (2019). Hypersonic boundary layer transition on a concave wall: stationary Görtler vortices. Journal of Fluid Mechanics, 865, 1-40.
Zhang C, Tang Q, Lee C (2013). Hypersonic boundary-layer transition on a flared cone. Acta Mechanica Sinica, 29 (1), 48-54.

There were 273 documents in this cluster with Chinese authors or co-authors published between 2012 and 2020. The following figures and tables provide an overview of Chinese research activity in the supersonic and hypersonic boundary layer cluster.

Figure 6. Growth in Chinese Research (2012 through 2020) – Boundary Layers

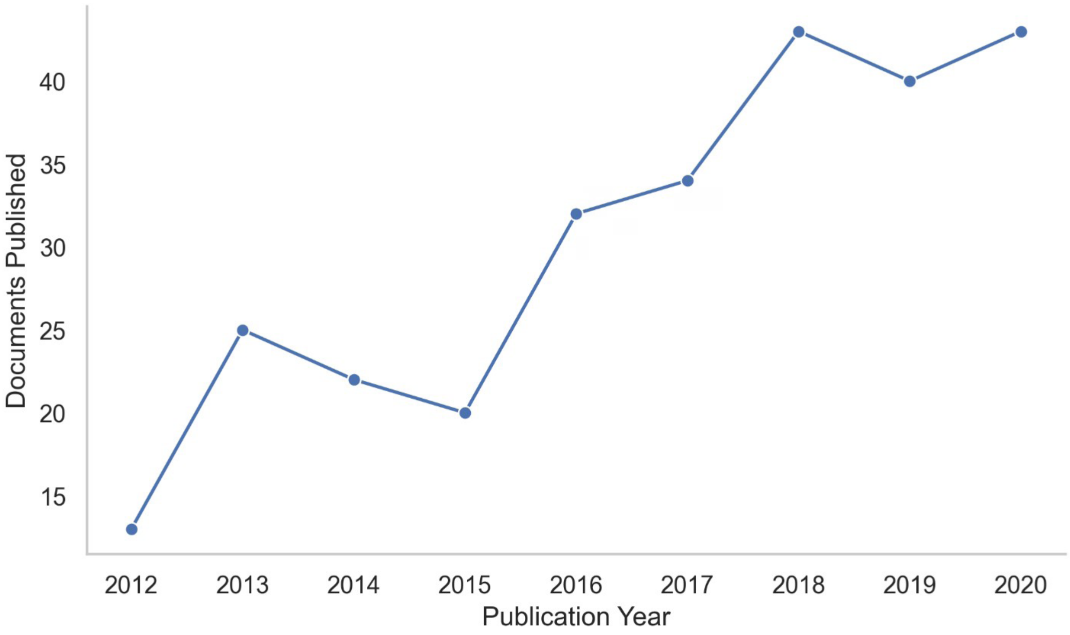


Table 14. Top Researchers – Boundary Layers

Name	Affiliation	Publication Count	Median Citations	H-Index
Fu Song	Tsinghua University	11	8	6
Lee Cunbiao	Peking University	9	24	6
Wang Qian-cheng	NUDT	9	6	5
She Zhen-Su	Peking University	9	5	5
Yan Chao	Beihang University	10	2	4

Table 15. Top Research Hubs – Boundary Layers

Name	Publication Count	Median Citations	H-Index
NUDT	38	5	10
Peking University	27	6	10
University of Science and Technology of China	14	10.5	9
Tsinghua University	27	4	8
Beihang University	26	2	8

2.2 PROPULSION TECHNOLOGY

2.2.1 Overview

Propulsion Technology is the most important of the six HV technology Groups in Cai and Xu's framework, as evidenced by the highest B1, B2 and B3 scores given. Cai and Xu's description of the Propulsion Technology Group is provided in the box below.

C2 - Propulsion Technology [推进技术**]**

The development of hypersonic vehicles must emphasize the guiding principle of "propulsion first." For hypersonic vehicles, breakthroughs in scramjet engines and the combined propulsion system are the focus of development. Scramjet engines present many problems, the first being the realization of supersonic combustion and the numerical simulation of super(sonic)-combustion, and the second the design and performance calculation of the inlet and exhaust nozzle. Matching the inlet and combustion chamber is also a very important issue in the research. The transition of sub-combustion and super-combustion working modes is also one of the technologies that need to be studied.

The above technologies can be further differentiated. For example, scramjet technology can be further broken down into inlet technology, combustion chamber technology, exhaust nozzle technology, flow passage integrated design technology, dual mode conversion technology, dual combustion room technology, etc. Combined propulsion system technologies include RBCC (Rocket-Based Combined Cycle) propulsion technology and TBCC (Turbine-Based Combined Cycle) propulsion technology. Energy bypass technology based on magnetohydrodynamics (MHD) can be classified as propulsion system control technology.

Cai and Xu, 32

Cai and Xu's component technology level ratings for the Propulsion Technology Group are provided below.

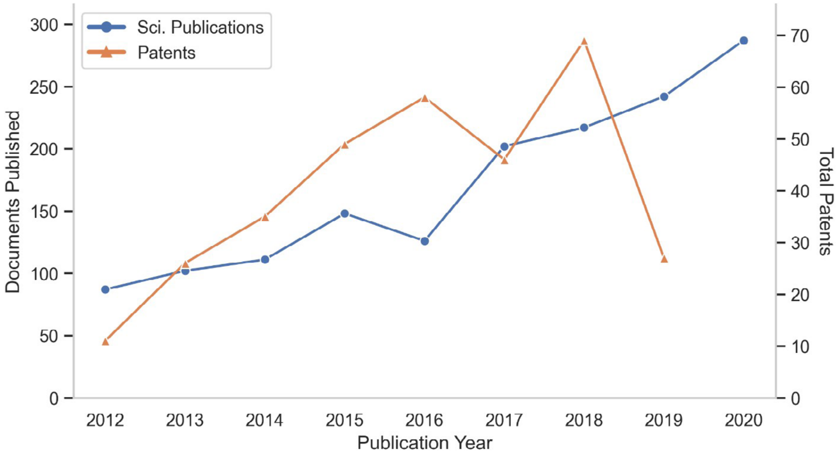
Table 17. Propulsion Technology Level Ratings

	Name of Technology	Value Assignment
C2-1	Scramjet engine technology [超燃冲压发动机技术]	9
C2-2	Combined propulsion system technology [组合推进系统技术]	5
C2-4	Hypersonic propulsion engine thermal structure and cooling technology [高超推进发动机热结构与冷却技术]	4
C2-3	Propulsion system control technology [推进系统控制技术]	3
C2-5	Endothermic hydrocarbon fuel technology [吸热型碳氢燃料技术]	2

The quantitative analysis mapped seven clusters containing 1,541 documents to the Propulsion Technology Group. A drill down is provided on the combustion in Super/hypersonic Engines and Shock/detonation Wave Studies Clusters. These clusters were selected for drill down due to their combination of activity, growth, and HV relevance. They are also relevant to Cai and Xu's C2-1 Scramjet Engine Technology and C2-2 combined Propulsion System Technology Groups, which had the highest value assignments in the HV development strategy. Figure 8 below shows research and patent activity over time in the Propulsion Technology Group.

Appendix 4: Patent Analysis for Propulsion Technology provides a sample of patents identified from this Group.

Figure 8. Patent Analysis for Propulsion Technology



The research output and patent activity in Propulsion Technology is consistent with the importance that Cai and Xu ascribed to it in 2012, but, as is shown in the cluster breakout to follow, the increase in research activity became prominent in 2016 in the relevant clusters. Chinese media reporting on hypersonic system development is fragmented and incomplete, likely due in part to the sensitivity of the technology; however, several events provide some insights into the bottlenecks and breakthroughs encountered.

One group, led by Jiang Zonglin [姜宗林], director of the CAS Institute of Mechanics' (IMECH) State Key Laboratory of High Temperature Gas Dynamics and an expert on hypersonic wind tunnel testing, encountered issues in scramjet development. Their prototype struggled to reach the speeds optimal for operation and experienced excessively high fuel consumption, making the technology unviable for use in commercial spaceplanes.[8] Frustrated with scramjet R&D, Jiang's team has pivoted to work on a different variation of engines for hypersonic flight publishing a study in the Chinese Journal of Aeronautics [中国航空学报] of a standing oblique detonation ramjet engine (sodramjet) that has demonstrated unprecedented performance in thrust, fuel efficiency and operational stability in wind tunnel testing, reaching nine times the speed of sound.[9] According to Jiang this breakthrough was inspired by a theory published by NASA in 1980.[10]

Another team working on scramjets for defense applications appears to have had more success. Major General Wang Zhenguo [王振国], an award-winning scientist at NUDT, is credited with "groundbreaking" achievements in scramjets and near-space flight vehicle design. In 2015, Wang and his team successfully developed what was described to be the world's first kerosene-burning scramjet with regenerative cooling [再生冷却超燃冲压发动机], which successfully underwent long-duration testing. Wang and his team are also credited with the design and development of China's first scramjet-powered hypersonic vehicle, which completed its first successful autonomous flight test in 2015.

Other sources suggest that despite these breakthroughs and the significant increase in activity since 2016, progress is uneven and overall scramjet R&D is slow compared to other countries. For example, writing in February 2019, researchers from the Chinese Ministry of Science & Technology's (MOST) High Technology Research and Development Center [科学技术部高技术研究发展中心] and Xi'an Jiaotong University suggest that there is a large gap between China's efforts and level of investment and other leading nations', especially in terms of research methods, equipment, funding, and personnel training.[11] They noted a need to enhance basic research in flame propagation and flame stability, detailed chemical reaction mechanism(s) of hydrocarbon fuel, and engine

2.2.2 Combustion in Super and Hypersonic Engines Cluster

This cluster focuses specifically on combustion within supersonic and hypersonic engines. The process of combustion requires a fuel and an oxidizer; controlling the rate of mixing, the efficiency of the mixing, and the mixture composition of these components is critical to achieve efficient combustion. Studies within this Group cover different fuel injection methods, various fuel composition, the thermal behavior of fuel (such as hydrocarbon cracking), and numerical methods to predict these behaviors.

Table 18. Representative Articles - Combustion

Relevant Articles
Choubey G, Yuvarajan D, Huang W, Yan L, Babazadeh H, Pandey K (2020). Hydrogen fuel in scramjet engines - A brief review. International Journal of Hydrogen Energy, 45 (33), 16799-16815.
Feng R, Zhu J, Wang Z, Sun M, Wang H, Cai Z, Yan W (2020). Dynamic characteristics of a gliding arc plasma-assisted ignition in a cavity-based scramjet combustor. Acta Astronautica, 171, 238-244.
Chen S, Zhao D (2019). RANS investigation of the effect of pulsed fuel injection on scramjet HyShot II engine. Aerospace Science and Technology, 84, 182-192.
Zhang J, Chang J, Ma J, Wang Y, Bao W (2019). Investigations on flame liftoff characteristics in liquid-kerosene fueled supersonic combustor equipped with thin strut. Aerospace Science and Technology, 84, 686-697.
Ren Z, Wang B, Xiang G, Zhao D, Zheng L (2019). Supersonic spray combustion subject to scramjets: Progress and challenges. Progress in Aerospace Sciences, 105, 40-59.
Liu B, He G, Qin F, An J, Wang S, Shi L (2019). Investigation of influence of detailed chemical kinetics mechanisms for hydrogen on supersonic combustion using large eddy simulation. International Journal of Hydrogen Energy, 44 (10), 5007-5019.
Sun M, Gong C, Zhang S, Liang J, Liu W, Wang Z (2012). Spark ignition process in a scramjet combustor fueled by hydrogen and equipped with multi-cavities at Mach 4 flight condition. Experimental Thermal and Fluid Science, 43, 90-96.
Wang Z, Sun M, Wang H, Yu J, Liang J, Zhuang F (2015). Mixing-related low frequency oscillation of combustion in an ethylene-fueled supersonic combustor. Proceedings of the Combustion Institute, 35 (2), 2137-2144.
Li X, Huang X, Liu H, Du J (2020). Fuel reactivity controlled self-starting and propulsion performance of a scramjet: A model investigation. Energy, 195, 116920.
Qiu H, Zhang J, Sun X, Chang J, Bao W, Zhang S (2020). Flowing residence characteristics in a dual-mode scramjet combustor equipped with strut flame holder. Aerospace Science and Technology, 99, 105718.

There were 646 documents in this cluster with Chinese authors or co-authors published from 2012 through 2020. In addition, there was a significant inflection point in 2016, with activity in this area greatly increasing thereafter. The following figures and tables provide an overview of Chinese research activity in the combustion in super and hypersonic engines cluster.

Figure 9. Growth in Chinese Research (2012 through 2020) – Combustion

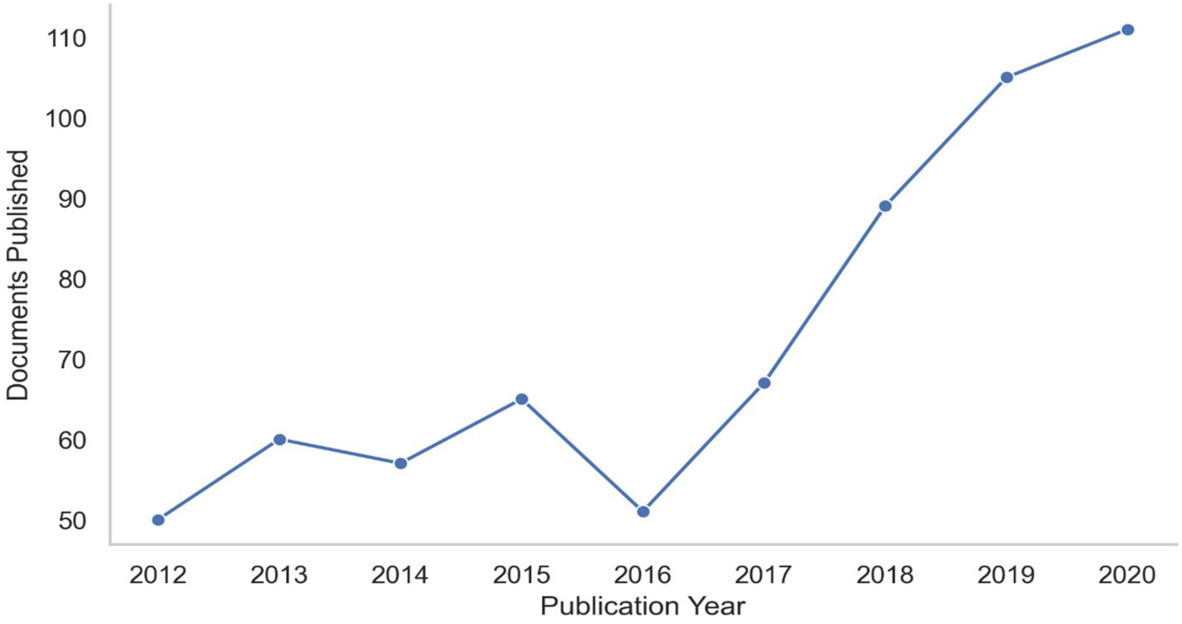


Table 19. Top Researchers – Combustion

Name	Affiliation	Publication Count	Median Citations	H-Index
Wang Zhenguo	NUDT	49	11	17
Sun Mingbo	NUDT	50	10	16
Bao Wen	Harbin Institute of Technology	37	14	16
Chang Juntao	Harbin Institute of Technology	27	19	16
Wang Hongbo	NUDT	33	9	12

Table 20. Top Research Hubs – Combustion

Name	Publication Count	Median Citations	H-Index
NUDT	125	7	24
Northwestern Polytechnical University	81	2	15
Harbin Institute of Technology	70	9	17
Chinese Academy of Sciences	43	4	11
Beihang University	43	6	11

Table 21. Top Collaborations – Combustion

Name	Country	Publication Count	Median Citations
Lund University	Sweden	8	23
University of Canterbury	New Zealand	8	14
Ton Duc Thang University	Vietnam	8	3
Khazar University	Azerbaijan	8	3
University of Leeds	United Kingdom	5	30

2.2.3 Shock and Detonation Wave Studies Cluster

Sodramjets have two main modes of operation: shock-induced combustion and detonation combustion. This cluster features studies that focus on accurately characterizing these processes through new visualization and measuring techniques, modifications and features that change the characteristics of these combustion processes, or numerical methods that aim to accurately predict these combustion processes given certain conditions. Table 22 shows representative articles from this cluster that had high HV relevance.

Table 22. Representative Articles –Wave Studies

Relevant Articles
Huang W, Wu H, Yang Y, Yan L, Li S (2020). Recent advances in the shock wave/boundary layer interaction and its control in internal and external flows. Acta Astronautica, 174, 103-122.
Wu K, Zhang S, Luan M, Wang J (2020). Effects of flow-field structures on the stability of rotating detonation ramjet engine. Acta Astronautica, 168, 174-181.
Tan H, Sun S, Huang H (2012). Behavior of shock trains in a hypersonic inlet/isolator model with complex background waves. Experiments in Fluids, 53 (6), 1647-1661.
Yang P, Ng H, Teng H (2019). Numerical study of wedge-induced oblique detonations in unsteady flow. Journal of Fluid Mechanics, 876, 264-287.
Meng X, Ye Z, Hong Z, Ye K (2020). Influences of wall vibration on shock train structures and performance of two-dimensional rectangular isolators in scramjet engine. Acta Astronautica, 166, 180-198.
Yang P, Ng H, Teng H, Jiang Z (2017). Initiation structure of oblique detonation waves behind conical shocks. Physics of Fluids, 29 (8), 086104.
Su W, Chen Y, Zhang F, Tang P (2018). Control of pseudo-shock oscillation in scramjet inlet-isolator using periodical excitation. Acta Astronautica, 143, 147-154.
Li N, Chang J, Xu K, Yu D, Bao W, Song Y (2017). Prediction dynamic model of shock train with complex background waves. Physics of Fluids, 29 (11), 116103.
Shi W, Chang J, Zhang J, Ma J, Wang Z, Bao W (2019). Numerical investigation on the forced oscillation of shock train in hypersonic inlet with translating cowl. Aerospace Science and Technology, 87, 311-322.
Xiang G, Li X, Sun X, Chen X (2019). Investigations on oblique detonations induced by a finite wedge in high altitude. Aerospace Science and Technology, 95, 105451.

There were 408 documents in this cluster with Chinese authors or co-authors published between 2012 and 2020. In addition, there was an inflection point in 2016, with activity in this area greatly increasing thereafter. The following figures and tables provide an overview of Chinese research activity in the shock and detonation wave studies cluster.

Figure 10. Growth in Chinese Research (2012 through 2020) – Wave Studies

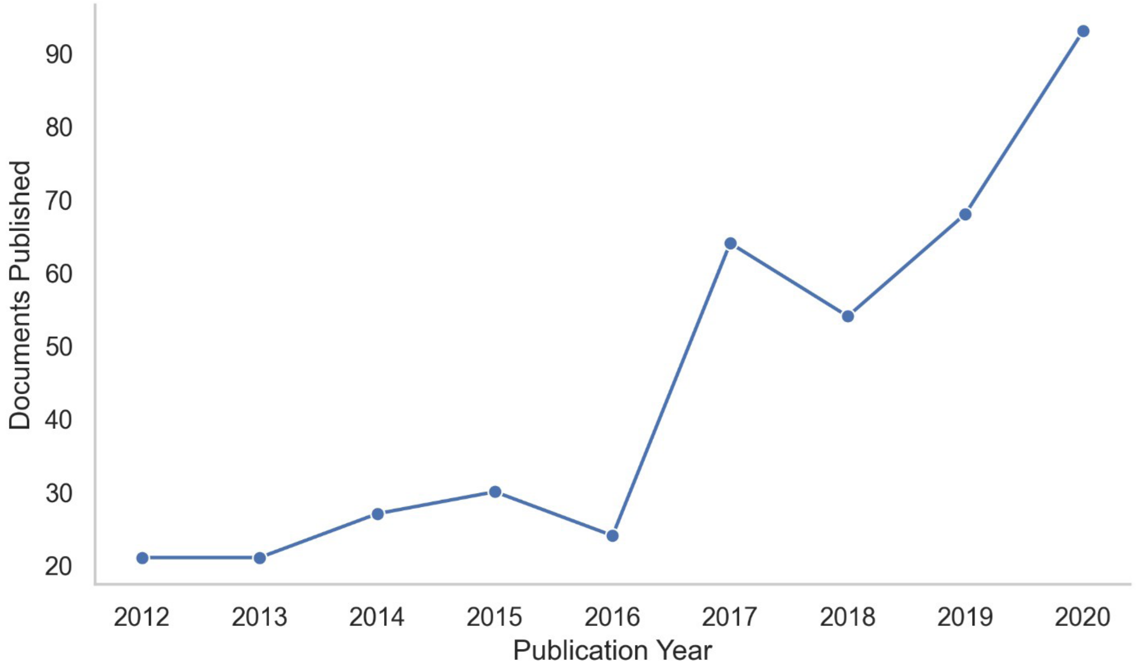


Table 23. Top Researchers – Wave Studies

Name	Affiliation	Publication Count	Median Citations	H-Index
Zhang Bo	Shanghai Jiao Tong University	20	31	16
Liu Shijie	NUDT	21	12	11
Teng Honghui	Beijing Institute of Technology	19	17	11
Lin Zhiyong	NUDT	16	18	12
Jiang Zonglin	Chinese Academy of Sciences	17	23	9

Table 24. Top Research Hubs – Wave Studies

Name	Publication Count	Median Citations	H-Index
NUDT	60	6	15
Chinese Academy of Sciences	41	6	15
Beijing Institute of Technology	40	9	16
University of Science and Technology of China	36	3	9
Tsinghua University	34	5	10

Figure 11. Chinese International Collaborative Intensity – Wave Studies

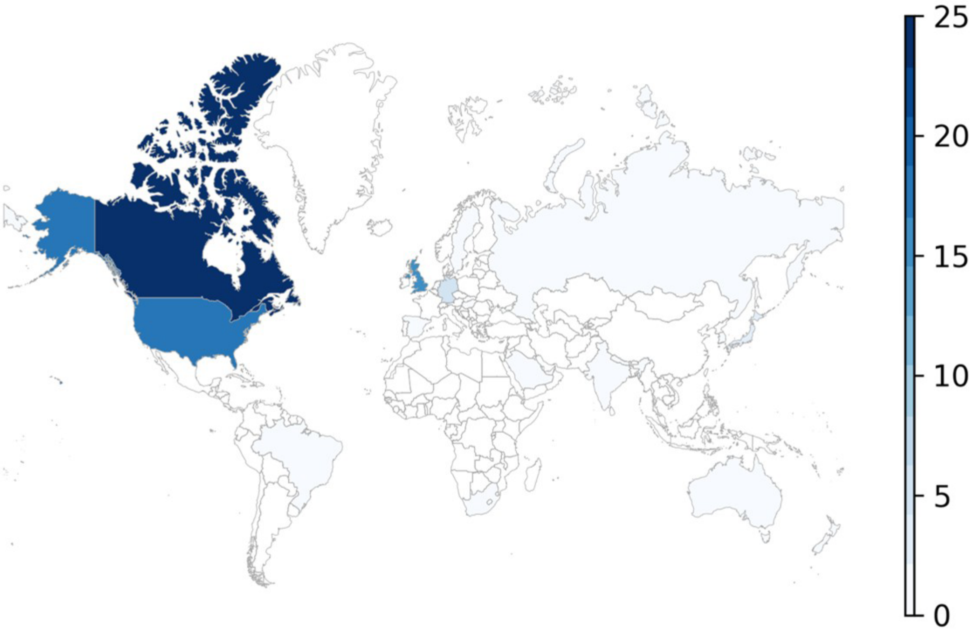


Table 25. Top Five International Collaborators – Wave Studies

Name	Country	Publication Count	Median Citations
Concordia University	Canada	21	27
McGill University	Canada	6	21
University of Southampton	United Kingdom	5	9
University of the West of England	United Kingdom	3	18
Princeton University	United States	3	4

2.3 MATERIALS, PROCESSING, AND MANUFACTURING TECHNOLOGIES

2.3.1 Overview

Materials, Processing, and Manufacturing Technology has the lowest assignment value from Cai and Xu, primarily because this technology Group is not specific to HV. Cai and Xu's description of the Materials, Processing, and Manufacturing Technology Group is provided in the box below.

C3 – Materials, Processing, and Manufacturing Technologies [材料/工艺/制造艺术]
The problem of aerodynamic heating of hypersonic vehicles brought new challenges in the research and development of heat-resistant materials and the design of heat-resistant structures. Heat is not the only issue. To increase the size of the payload, it is necessary to develop lightweight materials while meeting strength and heat resistance requirements.

Cai and Xu, 32

Cai and Xu's component technology level ratings for the Materials/Processing/ManufacturingTechnology Group are provided below.

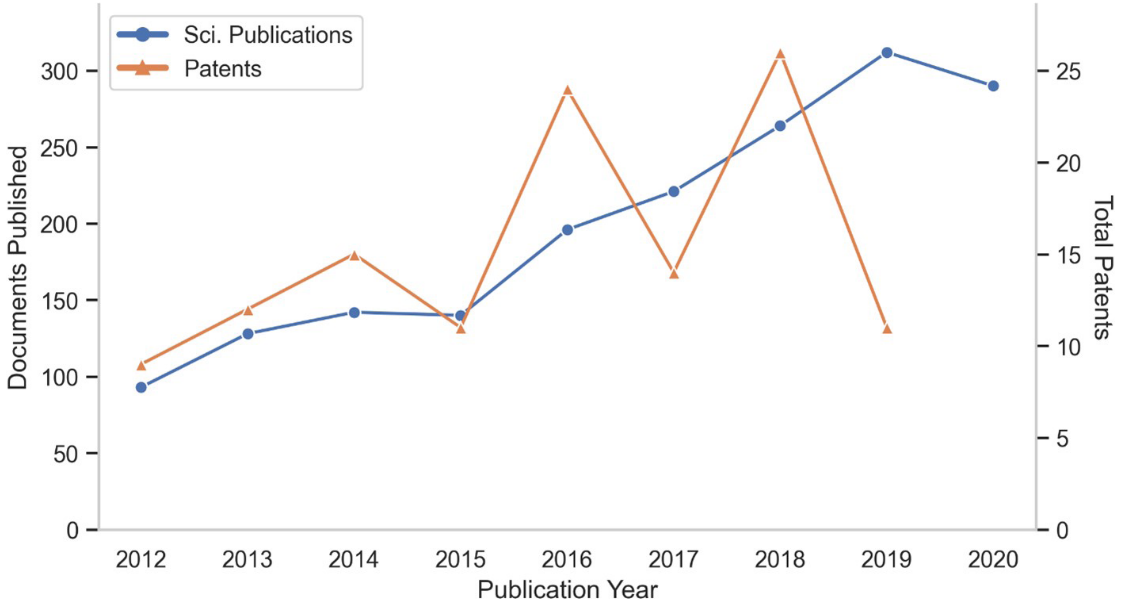
Table 26. Materials, Processing, and Manufacturing Technology Level Ratings

	Name of Technology	Value Assignment
C3-1	Heat-resistant and thermal insulation materials [防热与隔热材料)	2
C3-2	Heat-resistant coating materials [防热涂层材料]	1
C3-5	Component joining, welding and sealing technology [部件连接、焊接与密封技术]	1
C3-3	Light(weight) high-strength materials [轻质高强度材料]	1
C3-4	Atypical structural design and shaping technology [异型结构设计与成型技术]	1

Appendix 5: Patent Analysis for Materials / Processing / Manufacturing Technology Group provides a sample of patents of patents identified from the this Group.

The materials technology category encompasses the materials, metals, and substances used in the construction and design of hypersonic vehicles. The quantitative analysis found 1,803 documents and 10 clusters relevant to this Group. The preponderance of HV specific terms in the articles was quite low (relative to the Propulsion cluster, for example). This is because while research in these clusters is relevant to HV development, it is also important to other areas of scientific inquiry. Cai and Xu gave technologies in this Group a low value assignment due to this dynamic. A drill down is provided on the Thermal Shock Resistance in Ceramics Cluster and High Temperature Oxidation Resistance Cluster which were selected due to their combination of activity, growth, and their relevance to Cai and Xu's C3-2 Heat-resistant coating materials. Figure 12 below shows research and patent activity over time in the Materials/Processing/ Manufacturing Technology Group.

Figure 12. Materials, Processing, and Manufacturing Research and Patent Activity



2.3.2 High Temperature (HT) Oxidation Resistance in Ceramics and Alloys Cluster

Vehicles traveling at supersonic and hypersonic speeds experience high levels of friction heating from air resistance. Materials used in hypersonic vehicles must have high temperature resistance and designs must facilitate effective heat management. Studies within this cluster report on the synthesis of various composite and alloy materials, their oxidation and ablation resistance, and their thermal management properties. Table 27 shows representative articles from this cluster that had high HV relevance.

Table 27. Representative Articles – HT Oxidation Resistance Cluster

Relevant Articles
Qu S, Tang S, Feng A, Feng C, Shen J, Chen D (2018). Microstructural evolution and high-temperature oxidation mechanisms of a titanium aluminide based alloy. Acta Materialia, 148, 300-310.
Zeng Y, Wang D, Xiong X, Zhang X, Withers P, Sun W, Smith M, Bai M, Xiao P (2017). Ablation-resistant carbide $Zr_{0.8}Ti_{0.2}C_{0.74}B_{0.26}$ for oxidizing environments up to 3,000°C, Nature Communications, 8 (1), 15836-15836.
Niu J, Jin H, Meng S, Qingxuan Z, Peng Z (2016). ZrO_2-induced crack-healing mechanism of ZrB_2–SiC–Graphite composite in high temperature atomic oxygen environment. Ceramics International, 42 (4), 5562-5568.
Wang R, Li W (2017). Determining fracture strength and critical flaw of the ZrB_2–SiC composites on high temperature oxidation using theoretical method. Composites Part B-engineering, 129, 198-203.
Li D, Yang Z, Jia D, Duan X, Cai D, He P, Wang S, Zhou Y (2020). Dense amorphous $Si_2BC_{1-4}N$ monoliths resistant to high-temperature oxidation for hypersonic vehicle. Corrosion Science, 163, 108231.
Chen Z, Yong W, Chen Y, Wang H, Zeng Y, Xiong X (2020). Preparation and oxidation behavior of Cf/C–TaC composites. Materials Chemistry and Physics, 254, 123428.
Key A (2014). Calculation of Nitric Oxide's Infrared Radiative Parameters under High Temperature. Acta Optica Sinica
Wang R (2017). Determining fracture strength and critical flaw of the ZrB_2–SiC composites on high temperature oxidation using theoretical method. The 8th International Conference on Computational Methods (ICCM2017).

There were 199 documents in this cluster with Chinese authors or co-authors published between 2012 and

2020. The following figures and tables provide an overview of Chinese research activity in the High Temperature Oxidation Resistance in Ceramics and Alloys Cluster.

Figure 13. Growth in Chinese Research (2012 through 2020) – HT Oxidation Resistance Cluster

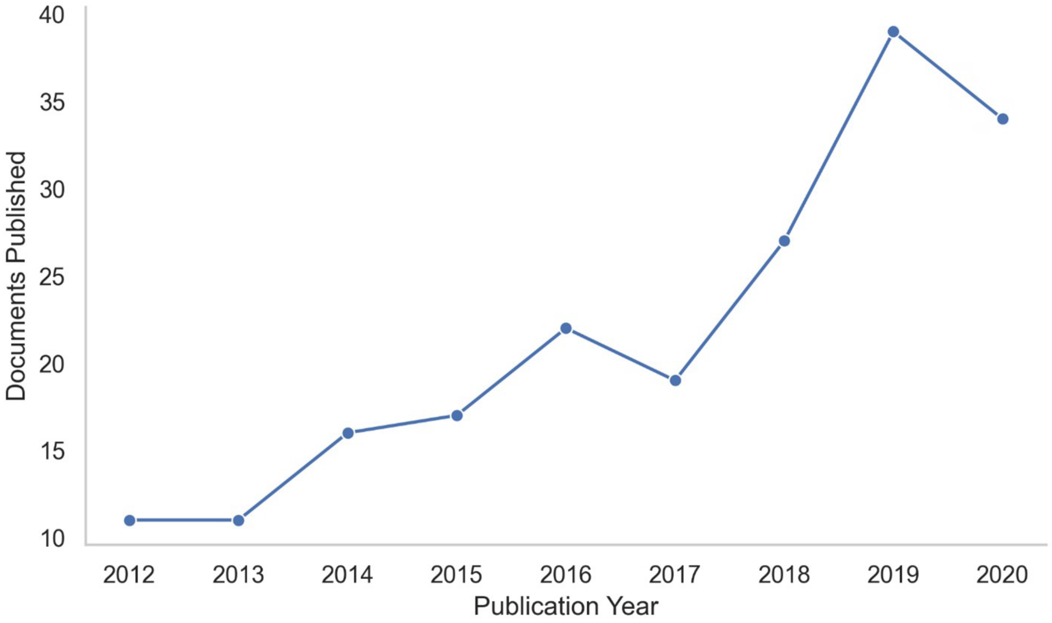


Table 28. Researchers – HT Oxidation Resistance Cluster

Name	Affiliation	Publication Count	Median Citations	H-Index
Fu Qiangang	Northwestern Polytechnical University	15	6	7
Zhang Xinghong	Harbin Institute of Technology	10	12	7
Li Hejun	Northwestern Polytechnical University	8	54	7
Yang Zhihua	Harbin Institute of Technology	8	11	5
Jia Dechang	Harbin Institute of Technology	8	11	5

Table 29. Top Research Hubs – HT Oxidation Resistance Cluster

Name	Publication Count	Median Citations	H-Index
Northwestern Polytechnical University	34	9	14
Harbin Institute of Technology	33	8	12
Chinese Academy of Sciences	27	10	12
Beihang University	10	27	10
NUDT	9	11	7

Figure 14. Chinese International Collaborative Intensity – HT Oxidation Resistance Cluster

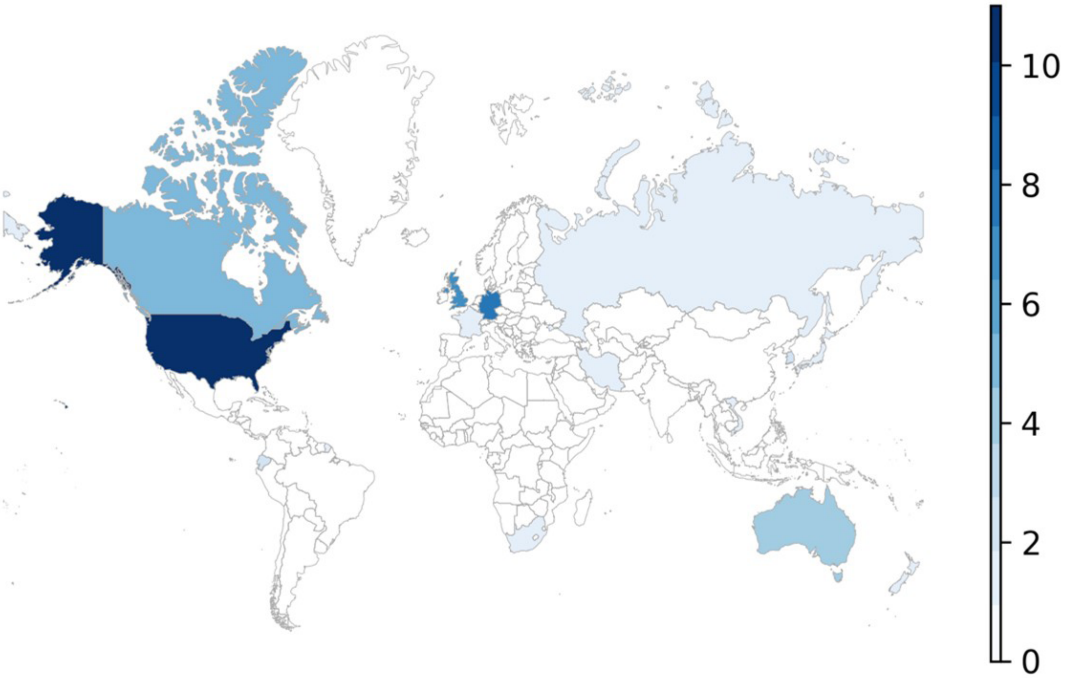


Table 30. Top Five International Collaborators – HT Oxidation Resistance Cluster

Name	Country	Publication Count	Median Citations
Ryerson University	Canada	4	7
Technische Universiteit Darmstadt	Germany	5	1
Curtin University	Australia	3	15
University of Wisconsin-Madison	United States	3	55
University of Manchester	United Kingdom	3	9

2.3.4 Thermal Shock Resistance in Ceramics Cluster

Thermal shock is a phenomenon that occurs when a material is exposed to a rapid and drastic temperature gradient inducing a rapid and often asymmetric expansion of the material causing the material to fail. Combustion engines and supersonic flight present these types of conditions. Research within this cluster focus on the preparation and characterization of various ceramic materials and their behavior when exposed to thermal shock inducing conditions. Table 31 shows representative articles from this cluster that had HV relevance.

Table 31. Representative Articles – Thermal Shock Resistance Cluster

Representatitve Artices
Zhang B, Huang H, Lu X (2019). Fabrication and properties of C/SiC porous ceramics by grinding-mould pressing-sintering process. Journal of The European Ceramic Society, 39 (5), 1775-1780.
Wang B, Li J (2020). Fracture behavior and thermal shock resistance analysis of thermoelectric material plates and shells under thermal and electric shocks. Engineering Fracture Mechanics, 225, 106130.
Zhang M, Yang G, Zhang L, Zhang Y, Yin J, Ma X, Wen J, Linglu D, Wang X, Chen H, Zhang L, Yin L, Jian X, Zhao X, Deng L (2020). Application of ZrB2 thin film as a low emissivity film at high temperature. Applied Surface Science, 527, 146763.
Zhou Y, Dai F, Xiang H, Liu B, Feng Z (2017). Shear anisotropy: Tuning high temperature metal hexaborides from soft to extremely hard. Journal of Materials Science & Technology, 33 (11), 1371-1377.
Liu Z, Sun Q, Song Y, Yang J, Chen X, Wang H, Jiang Z (2018). High-emissivity composite-oxide fillers for high temperature stable aluminumchromium phosphate coating. Surface & Coatings Technology, 349, 885-893.
Chen H, Xiang H, Dai F, Liu J, Zhou Y (2019). High strength and high porosity YB2C2 ceramics prepared by a new high temperature reaction/ partial sintering process. Journal of Materials Science & Technology, 35 (12), 2883-2891.
Lin L, Wu D, Ren H, Zhu F (2019). Thermal shock fracture behavior of wave-transparent brittle materials in hypersonic vehicles under high thermal flux by digital image correlation. Optics Express, 27 (7), 10269-10279.
Shang L, Wu D, Pu Y, Wang H, Wang F, Gao Z (2016). Experimental research on thermal insulation performance of lightweight ceramic material in oxidation environment up to 1700 °C. Ceramics International, 42 (2), 3351-3360.
Wu D, Lin L, Ren H (2020). Thermal/vibration joint experimental investigation on lightweight ceramic insulating material for hypersonic vehicles in extremely high-temperature environment up to 1500 °C. Ceramics International, 46 (10), 14439-14447.

There were 206 documents in this cluster with Chinese authors or co-authors published between 2012 through 2020. The following figures and tables provide an overview of Chinese research activity in the Thermal Shock Resistance in Ceramics Cluster.

Figure 15. Growth in Chinese Research (2012 through 2020) – Thermal Shock Resistance Cluster

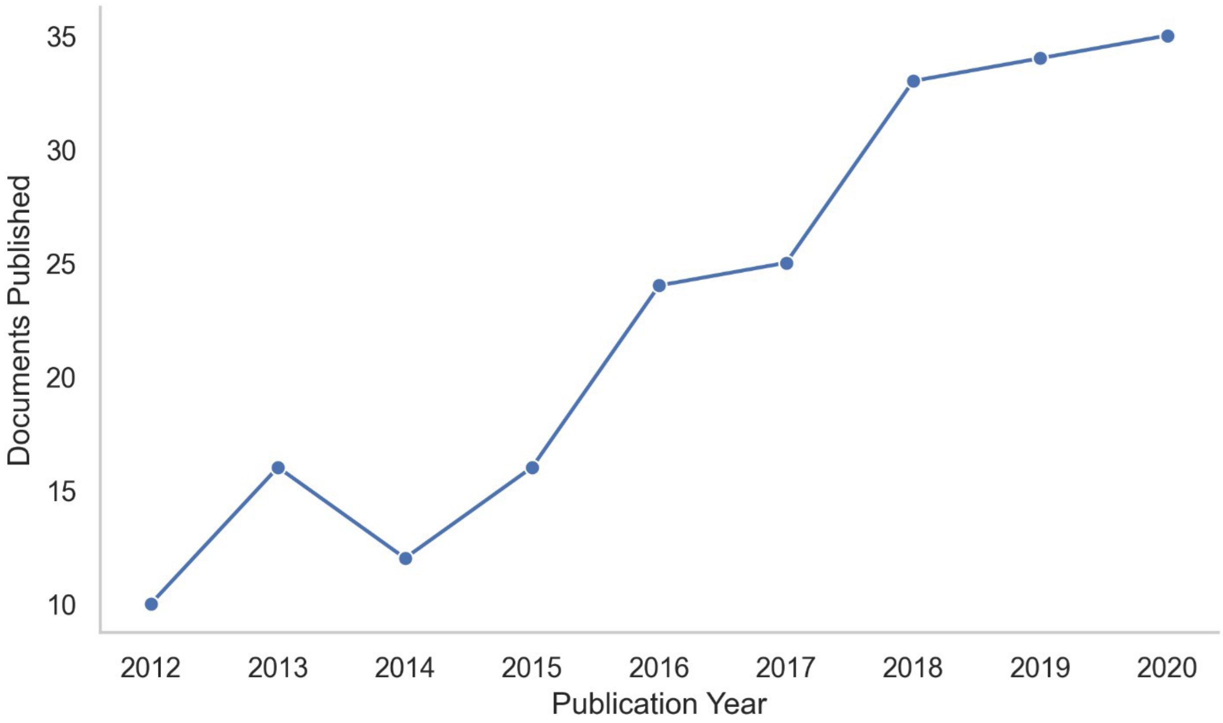


Table 32. Top Researchers – Thermal Shock Resistance Cluster

Name	Affiliation	Publication Count	Median Citations	H-Index
Fang Daining	Beijing Institute of Technology	12	14	8
Liu Jiachen	Tianjin University	12	9	6
Li Weiguo	Chongqing University	12	6	6
Zhang Xinghong	Harbin Institute of Technology	8	15	7
He Rujie	Beijing Institute of Technology	7	20	7

Table 33. *Top Research Hubs – Thermal Shock Resistance Cluster*

Name	Publication Count	Median Citations	H-Index
Harbin Institute of Technology	36	10	13
Chinese Academy of Sciences	25	9	10
Northwestern Polytechnical University	21	9	10
Chongqing University	17	8	8
Tianjin University	15	10	8

Figure 16. Chinese International Collaborative Intensity – Thermal Shock Resistance Cluster

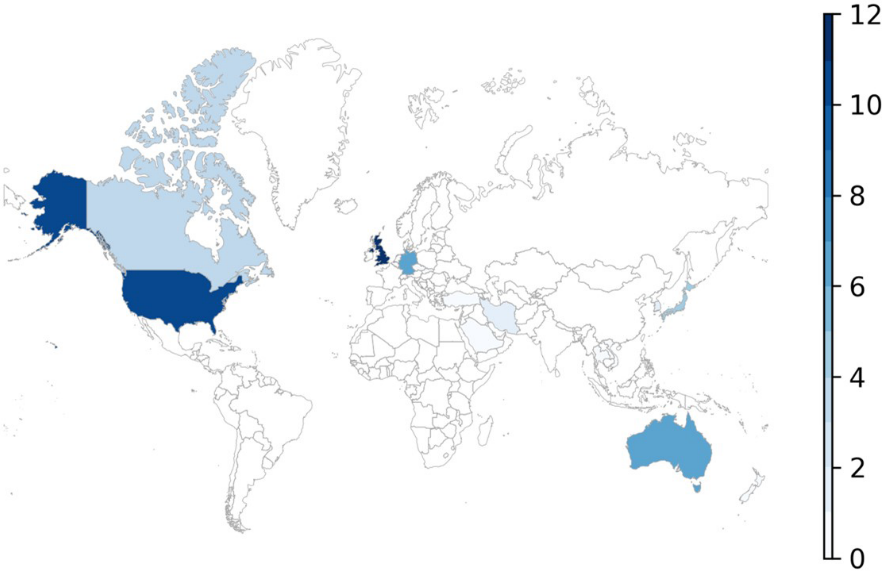


Table 34. *Top Five International Collaborators – Thermal Shock Resistance Cluster*

Name	Country	Publication Count	Median Citations
Iowa State University	United States	3	48
University of Sydney	Australia	4	8
University of Birmingham	United Kingdom	3	17
University of Mohaghegh Ardabili	Iran	2	41
Seoul National University	South Korea	2	41

2.4 TESTING AND VERIFICATION TECHNOLOGY

2.4.1 Overview

Testing and Verification Technology is the third most important of the six technology Groups. Cai and Xu gave it the second highest B1 rating (unique to HV, after propulsion). Cai and Xu's description of the Testing and Verification Technology Group is provided in the box below.

C4 - Testing and Verification Technology [试验验证技术]
Testing and verification technology is the key to moving from theory to practical application. For hypersonic vehicles this mainly includes supersonic combustion tests, free jet model engine tests, and flight vehicle aerodynamic and aerodynamic heating wind tunnel tests, as well as related test methods, data measurement and processing, and other issues.

Cai and Xu, 32

Cai and Xu's component technology level ratings for the Testing and Verification Technology Group are provided below.

Table 35. Testing and Verification Technology Level Ratings

	Name of Technology	Value Assisgment
C4-1	Direct-connected super-combustion chamber testing technology [直连式超燃燃烧室试验技术]	3
C4-2	Scramjet engine free jet testing technology [超燃冲压发动机自由射流试验技术]	3
C4-5	Hypersonic aircraft aerodynamic testing technology [高超声速飞行器气动力试验技术]	2
C4-3	Combined propulsion systems testing technology [组合推进系统试验技术]	2
C4-6	Hypersonic vehicle aerodynamic heating testing technology [高超声速飞行器气动热试验技术]	2
C4-4	Hypersonic wind tunnel technology [高超声速风洞技术]	2
C4-7	Heat-resistant structural materials thermal environment simulation and testing technology [防热结构材料热环境模拟与试验技术]	1

The testing and verification technology category was one of two categories where representation within published hypersonic-related works was sparse, the other being category C6, flight demonstration and validation technology. The common element in these two categories is that they are more applied in nature which may increase their sensitivity resulting in the low number of journal articles found. There were 167 patents relevant to the Testing and Verification Group examples of which are provided in Appendix 7.

Only one cluster of 72 documents was identified as relevant to this category. The central theme of this cluster was supersonic, hypersonic, and shock wind tunnel technology, which is pertinent to Cai and Xu's C4-4 Hypersonic Wind Tunnel Technology. Table 36 shows representative articles from this cluster that had HV relevance.

Table 36. Representative Articles – Wind Tunnel Technology

Representative Articles
Shi M, Zhu W, Lee C (2020). Engineering Model for Transition Prediction Based on a Hypersonic Quiet Wind Tunnel. AIAA Journal, 58 (8), 3476-3485.
Jiao X, Chang J, Wang Z, Yu D (2017). Numerical study on hypersonic nozzle-inlet starting characteristics in a shock tunnel. Acta Astronautica, 130, 167-179.
Jiang Z (2014). Experiments and development of Long-test-duration Hypervelocity Detonation-driven Shock Tunnel (LHDst). 52nd Aerospace Sciences Meeting, , .
Peng D, Jiao L, Sun Z, Gu Y, Liu Y (2016). Simultaneous PSP and TSP measurements of transient flow in a long-duration hypersonic tunnel. Experiments in Fluids, 57 (12), 188.
Luo K, Wang Q, Li J, Li J, Zhao W (2020). Numerical modeling of a high-enthalpy shock tunnel driven by gaseous detonation. Aerospace Science and Technology, 104, 105958.
Wang Q, Luo K, Li J, Li J, Zhao W (2020). Investigation of dual ignition for a detonation-driven shock tunnel in forward driving mode. Chinese Journal of Aeronautics, 33 (5), 1468-1475.
Liu Y, Wang Y, Yuan C, Luo C, Jiang Z (2017). Aerodynamic force and moment measurement of 10° half-angle cone in JF12 shock tunnel. Chinese Journal of Aeronautics, 30 (3), 983-987.
Yu K, Xu J, Li R, Liu S, Zhang X (2018). Experimental exploration of inlet start process in continuously variable Mach number wind tunnel. Aerospace Science and Technology, 79, 75-84.
Wang Y, Liu Y, Jiang Z (2016). Design of a pulse-type strain gauge balance for a long-test-duration hypersonic shock tunnel. Shock Waves, 26 (6), 835-844.
Baoqing M, Han G, Luo C, Jiang Z (2018). Numerical investigation of the axial impulse load during the startup in the shock tunnel. Aerospace Science and Technology, 73, 332-342.

The following figures and tables provide an overview of Chinese research activity in the Wind Tunnel Technology .

Table 37. Top Researchers – Wind Tunnel Technology

Name	Affiliation	Publication Count	Median Citations	H-Index
Jiang Zonglin	Chinese Academy of Sciences	11	1	3
Liu Yunfeng	Chinese Academy of Sciences	5	6	3
Wang Yunpeng	Chinese Academy of Sciences	7	3	3
Luo Changtong	Chinese Academy of Sciences	5	3	3
Jiang Zonglin	Chinese Academy of Sciences	1	24	1

Table 38. Top Research Hubs – Wind Tunnel Technology

Name	Publication Count	Median Citations	H-Index
Chinese Academy of Sciences	22	1	4
Nanjing University of Aeronautics and Astronautics	5	7	4
Shanghai Jiao Tong University	2	21	2
Harbin Institute of Technology	1	19	1
China Aerodynamics Research and Development Center	13	0	3

Figure 18. Chinese International Collaborative Intensity – Wind Tunnel Technology

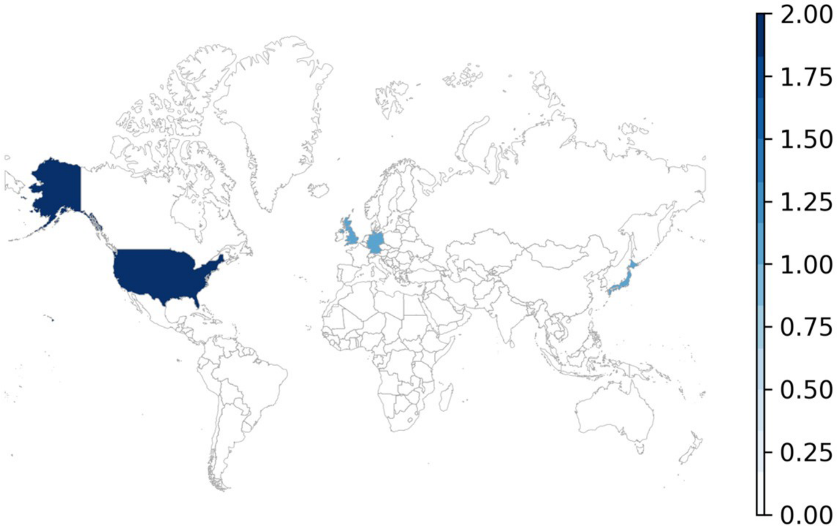


Table 39. Top Five International Collaborators – Wind Tunnel Technology

Name	Country	Publication Count	Median Citations
Braunschweig University of Technology	Germany	1	2
Northeastern University	United States	1	3
Osaka Institute of Technology	Japan	1	3
University of Glasgow	United Kingdom	1	3
Old Dominion University	United States	1	23

2.5 FLIGHT NAVIGATION, GUIDANCE, AND CONTROL TECHNOLOGY

2.5.1 Overview

Flight Navigation, Guidance, and Control Technology Group is the second least important of the six technology Groups. Cai and Xu gave it such a rating because similar to the materials Group, it has broad applicability to other areas of research unrelated to HV. Cai and Xu's description of the Flight Navigation, Guidance and Control Technology is provided in the box below.

C5 - Flight Navigation, Guidance, and Control Technology [飞行导航制导与控制技术**]**

Due to the characteristics of high-speed flight and the complex flight environment, the dynamics, control and guidance characteristics of hypersonic aircraft are quite different from traditional aircraft. It is necessary to conduct in-depth basic research into the complex mechanics.

The design of navigation system is one of the key technologies of hypersonic cruise aircraft, but it is increasingly difficult for a single navigation system to meet actual requirements. Various forms of integrated navigation systems containing a variety of navigation sensors have become the current main practical solutions and research directions for navigation systems.

Currently flight vehicles largely rely on optical sensors (including infrared and scene matching) and radars for guidance and navigation, and there is not enough research regarding combined techniques that would include, for example, inertial guidance systems.

The new generation of air defense flight vehicles must fundamentally improve the guidance accuracy, reduce the weight of the aircraft, and ensure that the aircraft has greater maneuverability. This set of requirements calls for the development of new technologies and improved techniques, an example being aerodynamic and direct lateral force control methods.

Cai and Xu, 274-275, 277, 280-281.

Cai and Xu's component technology level ratings for the Flight Navigation, Guidance, and Control Technology Group are provided below.

Table 40. Flight Navigation, Guidance, and Control Technology Level Ratings

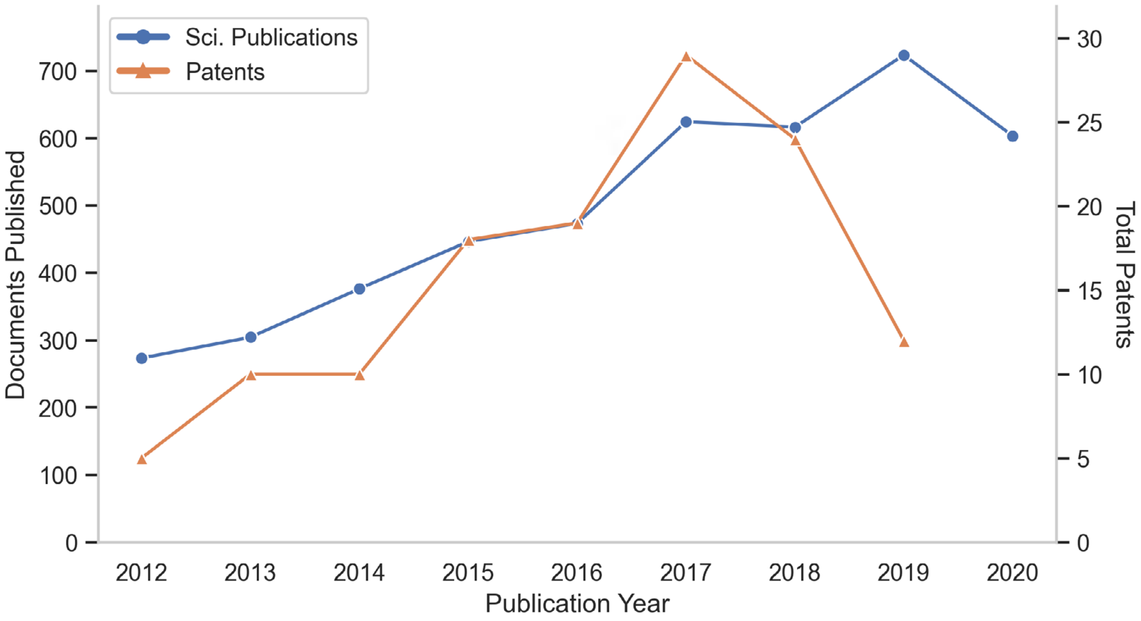
	Name of Technology	Value Assignment
C5-1	Hypersonic flight vehicle aerodynamics/ propulsion integrated control technology [高超声速飞行器气动/推进一体化控制技术]	2
C5-2	Hypersonic cruise vehicle navigation and control technology [高超声速巡航飞行器导航与控制技术]	1

C5-3	Hypersonic remote strike weapon precision guidance and control technology [高超声速远程打击武器精确制导与控制技术]	1

The flight navigation guidance and control technology category had the most documents mapped from the hypersonic clusters at 4,448 documents from 22 clusters. In general, we saw this in the clusters, but unlike in the materials technology Group, there were some clusters that were highly focused on HV development. A drill down is provided on the Adaptive, Fault-tolerant Control of HV Cluster and the Tracking Control Cluster due to their combination of activity, growth, and relevance to Cai and Xu's C5-2 Hypersonic cruise vehicle navigation and control technology [高超声速巡航飞行器导航与控制技术] and C5-3 Hypersonic remote strike weapon precision guidance and control technology [高超声速远程打击武器精确制导与控制技术] groups.

Figure 19 below shows research and patent activity over time in the Flight Navigation Guidance and Control Technology Group.

Figure 19. Flight Navigation, Guidance, and Control Technology Research and Patent Activity



Appendix 7: Patent Analysis for Flight Navigation, Guidance, and Control Technology Group provides a sample of patents identified from this Group.

2.5.2 Adaptive, Fault-tolerant Control of HV Cluster

Hypersonic vehicles operate under some of the most extreme conditions, which can present high risk of component failure and rapidly changing operational environments. To maintain consistent operation, fast and reliable control systems that can adapt to changing conditions and are respond effectively to faults are necessary. Publications within this Group discuss adaptive and fault-tolerant control schemes and systems for hypersonic vehicles. Table 41 shows representative articles from this cluster that had HV relevance.

Table 41. Representative Articles – Adaptive, Fault-tolerant Control

Representative Articles
Yuan Y, Wang Z, Guo L, Liu H (2020). Barrier Lyapunov Functions-Based Adaptive Fault-tolerant Control for Flexible Hypersonic Flight Vehicles With Full State Constraints. IEEE Transactions on Systems, Man, and Cybernetics, 50 (9), 3391-3400.
Xu B, Shi Z, Sun F, He W (2019). Barrier Lyapunov Function Based Learning Control of Hypersonic Flight Vehicle With AOA Constraint and Actuator Faults. IEEE Transactions on Systems, Man, and Cybernetics, 49 (3), 1047-1057.
Yu X, Li P, Zhang Y (2018). The Design of Fixed-Time Observer and Finite-Time Fault-Tolerant Control for Hypersonic Gliding Vehicles. IEEE Transactions on Industrial Electronics, 65 (5), 4135-4144.
Liu J, An H, Gao Y, Wang C, Wu L (2018). Adaptive Control of Hypersonic Flight Vehicles With Limited Angle-of-Attack. IEEE-ASME Transactions on Mechatronics, 23 (2), 883-894.
Dong C, Liu Y, Wang Q (2020). Barrier Lyapunov function based adaptive finite-time control for hypersonic flight vehicles with state constraints. Isa Transactions, 96, 163-176.
Yang J, Li S, Sun C, Guo L (2013). Nonlinear-Disturbance-Observer-Based Robust Flight Control for Airbreathing Hypersonic Vehicles. IEEE Transactions on Aerospace and Electronic Systems, 49 (2), 1263-1275.
Xu B, Wang D, Zhang Y, Shi Z (2017). DOB-Based Neural Control of Flexible Hypersonic Flight Vehicle Considering Wind Effects. IEEE Transactions on Industrial Electronics, 64 (11), 8676-8685.
Xu B (2015). Robust adaptive neural control of flexible hypersonic flight vehicle with dead-zone input nonlinearity. Nonlinear Dynamics, 80 (3), 1509-1520.
Liu C, Dong C, Zhou Z, Wang Z (2020). Barrier Lyapunov function based reinforcement learning control for air-breathing hypersonic vehicle with variable geometry inlet. Aerospace Science and Technology, 96, 105537.
An H, Wu Q, Wang C, Cao X (2020). Simplified fault-tolerant adaptive control of air-breathing hypersonic vehicles. International Journal of Control, 93 (8), 1964-1979.

There were 367 documents in this cluster with Chinese authors or co-authors published between 2012 and 2020. The following figures and tables provide an overview of Chinese research activity in the Adaptive, Fault-tolerant Control of HV Cluster.

Figure 20. Growth in Chinese Research (2012 through 2020) – Adaptive, Fault-tolerant Control

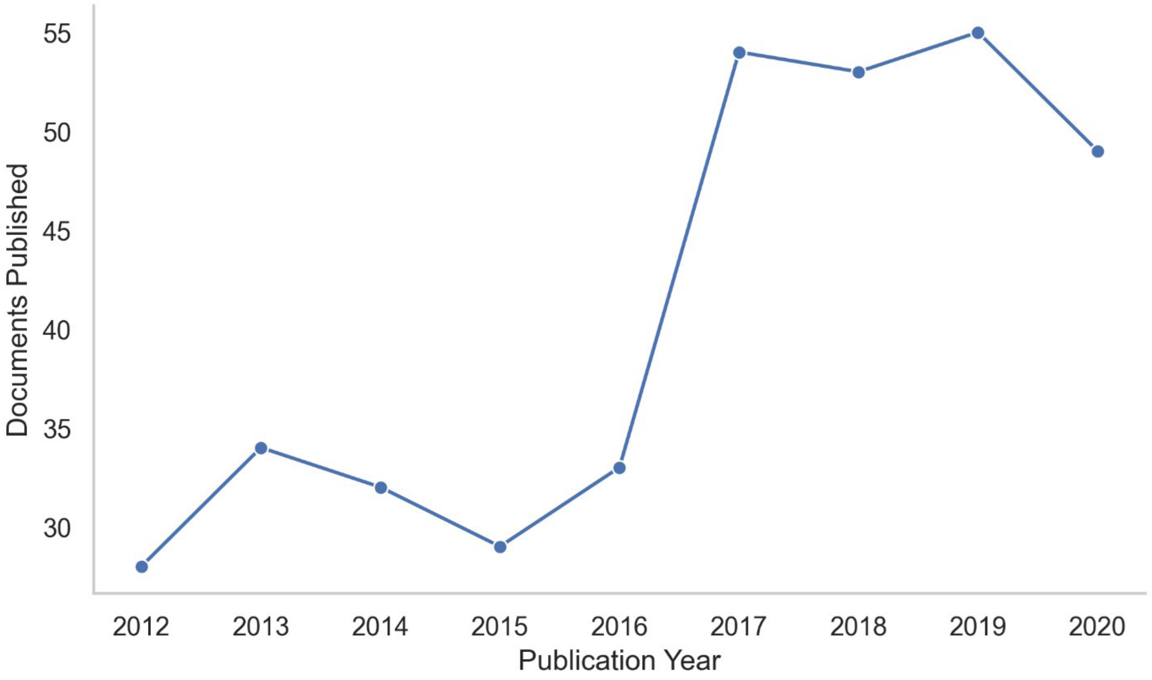


Table 42. Top Researchers – Adaptive, Fault-tolerant Control

Name	Affiliation	Publication Count	Median Citations	H-Index
Xu Bin	Northwestern Polytechnical University	13	49	7
An Hao	Harbin Institute of Technology	14	6	6
Jiang Bin	Nanjing University of Aeronautics and Astronautics	15	1	4
Hu Xiaosong	Chongqing University	1	263	1
Dong Chaoyang	Beihang University	8	6	5

Table 43. Top Research Hubs – Adaptive, Fault-tolerant Control

Name	Publication Count	Median Citations	H-Index
Beihang University	68	2	12
Northwestern Polytechnical University	47	3	11
Nanjing University of Aeronautics and Astronautics	64	1	9
University of Science and Technology Beijing	3	51	2
Harbin Institute of Technology	38	3	9

Figure 21. Chinese International Collaborative Intensity – Adaptive, Fault-tolerant Control

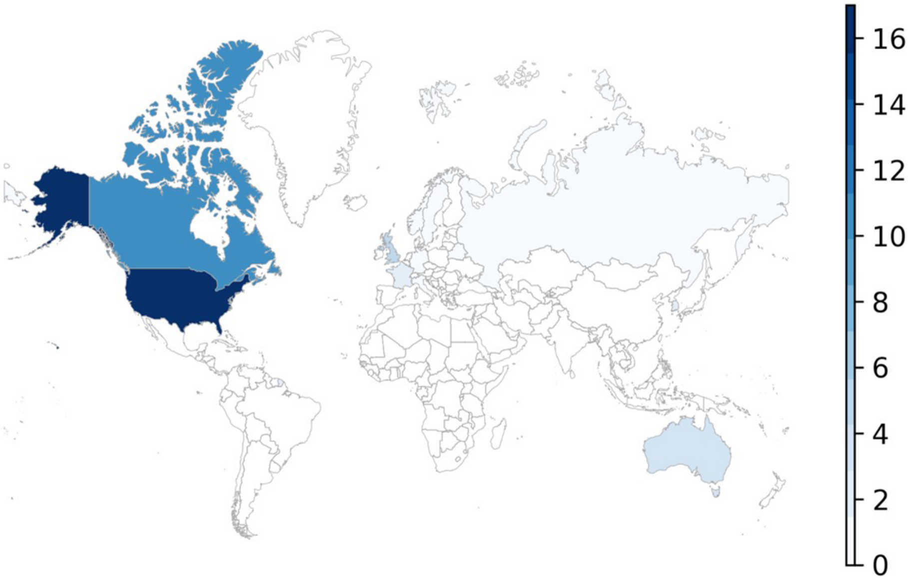


Table 44. Top Five International Collaborators – Adaptive, Fault-tolerant Control

Name	Country	Publication Count	Median Citations
Concordia University	Canada	8	25
University of Virginia	United States	6	6
Cranfield University	United Kingdom	1	263
Ohio State University	United States	1	141
Centre national de la recherche scientifique	France	1	104

2.5.3 Tracking Control Cluster

The ability to accurately predict and control hypersonic vehicle motion is a vital capability to successful hypersonic vehicle programs. This cluster focuses on various trajectory tracking control schemes and systems for hypersonic vehicles. Table 45 shows representative articles from this cluster that had HV relevance.

Table 45. Representative Articles – Tracking Control

Representative Articles
Wang Y, Yang X, Yan H (2019). Reliable Fuzzy Tracking Control of Near-Space Hypersonic Vehicle Using Aperiodic Measurement Information. IEEE Transactions on Industrial Electronics, 66 (12), 9439-9447.
Guo Z, Guo J, Zhou J, Chang J (2020). Robust Tracking for Hypersonic Reentry Vehicles via Disturbance Estimation-Triggered Control. IEEE Transactions on Aerospace and Electronic Systems, 56 (2), 1279-1289.
Wu L, Yang X, Li F (2013). Nonfragile Output Tracking Control of Hypersonic Air-Breathing Vehicles With an LPV Model. IEEE-ASME Transactions on Mechatronics, 18 (4), 1280-1288.
Wu H, Feng S, Liu Z, Guo L (2017). Disturbance observer based robust mixed H2/H fuzzy tracking control for hypersonic vehicles. Fuzzy Sets and Systems, 306, 118-136.
Shao X, Wang H (2016). Back-stepping robust trajectory linearization control for hypersonic reentry vehicle via novel tracking differentiator. Journal of The Franklin Institute-engineering and Applied Mathematics, 353 (9), 1957-1984.
Pu Z, Tan X, Fan G, Yi J (2014). Uncertainty analysis and robust trajectory linearization control of a flexible air-breathing hypersonic vehicle. Acta Astronautica, 101 (2014), 16-32.
Haibin D, Pei L (2012). Progress in control approaches for hypersonic vehicle. Science China-technological Sciences, 55 (10), 2965-2970.
Gao G, Wang J (2013). Reference command tracking control for an air-breathing hypersonic vehicle with parametric uncertainties. Journal of The Franklin Institute-engineering and Applied Mathematics, 350 (5), 1155-1188.

There were 315 documents in this cluster with Chinese authors or co-authors published between 2012 through 2020. The following figures and tables provide an overview of Chinese research activity in the Tracking Control Cluster.

Figure 22. Growth in Chinese Research (2012 through 2020) – Tracking Control

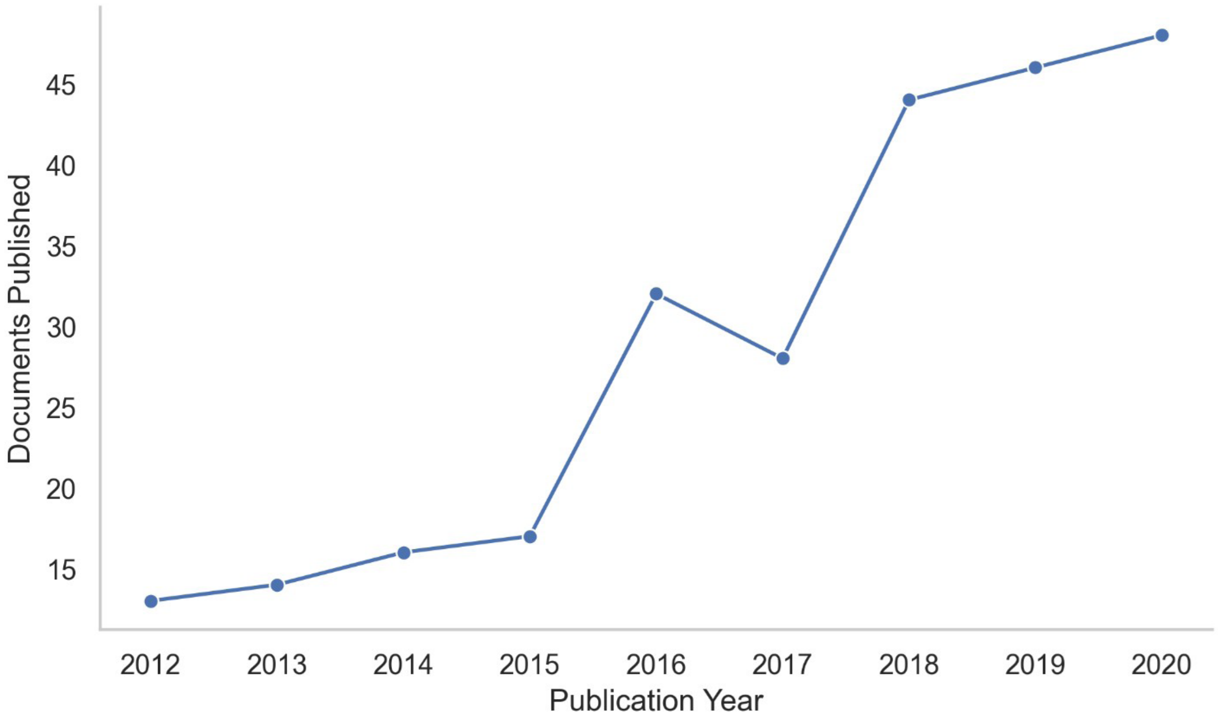


Table 46. Top Researchers – Tracking Control

Name	Affiliation	Publication Count	Median Citations	H-Index
Wang Ning	Dalian Maritime University	6	20	4
Shao Xingling	North University of China	6	10	4
Wang Honglun	Beihang University	4	28	4
Yu Shuanghe	Dalian Maritime University	4	12	4
Yan Yan	Dalian Maritime University	4	12	4

Table 47. Top Research Hubs – Tracking Control

Name	Publication Count	Median Citations	H-Index
Beihang University	37	8	16
Dalian Maritime University	19	8	9
Northwestern Polytechnical University	22	6	8
Nanjing University of Aeronautics and Astronautics	20	4	8
Beijing Institute of Technology	13	10	7

Figure 23. Chinese International Collaborative Intensity – Tracking Control

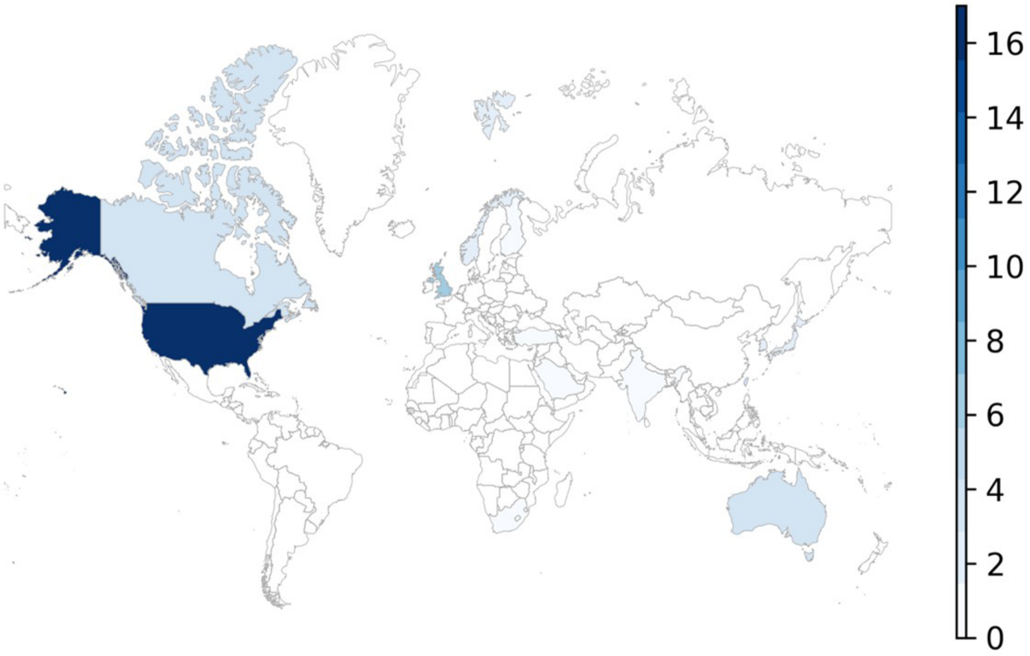


Table 48. Top Five International Collaborators – Tracking Control

Name	Country	Publication Count	Median Citations
Carl Albert State College	United States	1	0
Ritsumeikan University	Japan	1	0
University of Windsor	Canada	1	0
Mokpo National Maritime University	South Korea	1	0
Louisiana State University	United States	1	1

2.6 FLIGHT DEMONSTRATION AND VALIDATION TECHNOLOGY

2.6.1 Overview

Flight Demonstration and Validation Technology is the most fourth most important of the six technology Groups. Cai and Xu's description of the Flight Demonstration and Validation Technology Group is provided in the box below.

C5 - Flight Navigation, Guidance, and Control Technology [飞行导航制导与控制技术]
Due to the characteristics of high-speed flight and the complex flight environment, the dynamics, control and guidance characteristics of hypersonic aircraft are quite different from traditional aircraft. It is necessary to conduct in-depth basic research into the complex mechanics.
The design of navigation system is one of the key technologies of hypersonic cruise aircraft, but it is increasingly difficult for a single navigation system to meet actual requirements. Various forms of integrated navigation systems containing a variety of navigation sensors have become the current main practical solutions and research directions for navigation systems.
Currently flight vehicles largely rely on optical sensors (including infrared and scene matching) and radars for guidance and navigation, and there is not enough research regarding combined techniques that would include, for example, inertial guidance systems.
The new generation of air defense flight vehicles must fundamentally improve the guidance accuracy, reduce the weight of the aircraft, and ensure that the aircraft has greater maneuverability. This set of requirements calls for the development of new technologies and improved techniques, an example being aerodynamic and direct lateral force control methods.

Cai and Xu, 274-275, 277, 280-281.

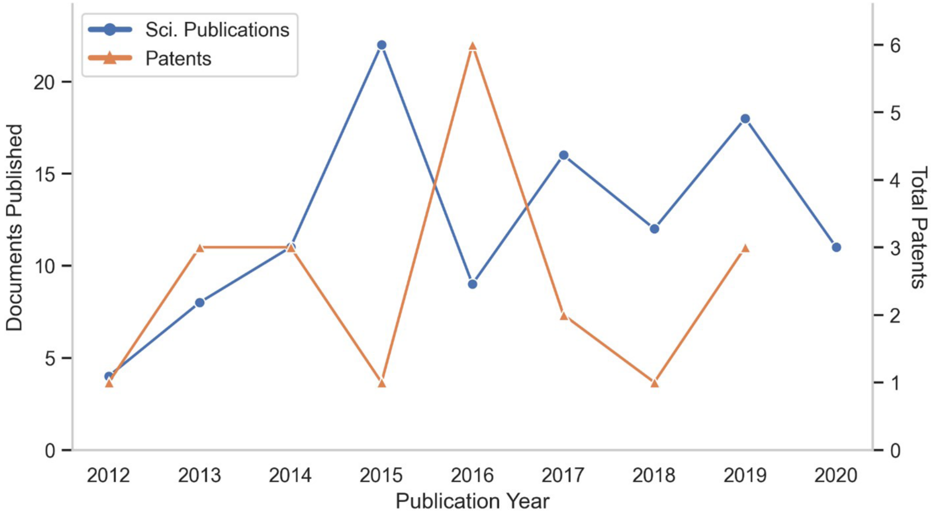
Cai and Xu's component technology level ratings for the Flight Demonstration and Validation Technology Group are provided below.

Table 49. Flight Demonstration & Validation Technology Level Ratings

	Name of Technology	Value Assignment
C6-4	Hypersonic separation technology [高超声速分离技术]	3
C6-5	Flight testing telemetry technology [飞行试验遥测技术]	2
C6-1	Flight testing risk assessment technology [飞行试验风险评估技术]	1
C6-2	Aerial launch technology [空中发射技术]	1
C6-3	Ground launch technology [地面发射技术]	1

Category C6 centered around the quality control of hypersonic vehicles, whereas previous topics are more oriented towards theory and design of general hypersonic flight or vehicles. No research clusters were found that map to this category. The lack of research publications in this area is unexpected given the progress China has made in hypersonic vehicles. One possible explanation is China is doing research in this domain, but that the work is classified and not published in the open source. Another explanation is that flight demonstration and validation is a more applied domain and may not be the subject of research-stage activities in China. Additional research would be needed to evaluate these hypotheses. Figure 24 below shows the patent activity over time in

Figure 24. Flight Demonstration and Validation Technology Patent Activity



2.7 NEW AREA OF RESEARCH – HYPERSONIC TARGET DETECTION

2.7.1 Overview

Cai and Xu did not include hypersonic target detection among the critical technologies in their HV development framework presumably because it was not relevant to their objective. The quantitative analysis found this cluster via the lexical and semantic search process. Although this cluster does not align to the HV development framework, it is relevant to Chinese hypersonic research activity and therefore was retained. This cluster was small with 111 documents and slow growth indicating that this is not a high priority for China.

Figure 25. Hypersonic Target Detection Research and Patent Acitivity

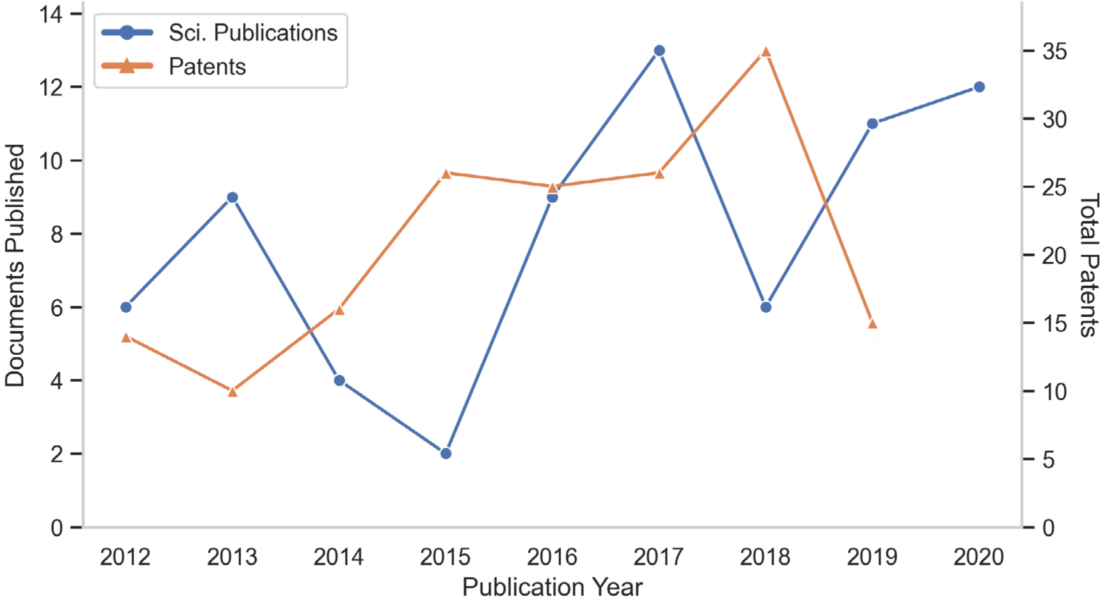


Table 50 shows representative articles from this cluster that had HV relevance.

Table 50. Representative Articles – Target Detection Cluster

Relevant Articles
Wu W, Wang G, Sun J (2018). Polynomial Radon-Polynomial Fourier Transform for Near Space Hypersonic Maneuvering Target Detection. IEEE Transactions on Aerospace and Electronic Systems, 54 (3), 1306-1322.
Wang Y, Cao Y, Wang S, Su H (2019). Clutter suppression and ground moving target imaging approach for hypersonic vehicle borne multichannel radar based on two-step focusing method. Digital Signal Processing, 85, 62-76.
Wang Y, Cao Y, Peng Z, Su H (2017). Clutter suppression and moving target imaging approach for multichannel hypersonic vehicle borne radar. Digital Signal Processing, 68, 81-92.
Liu S, Guo L, Pan W, Chen W, Xiao Y (2018). PO calculation for reduction in radar cross section of hypersonic targets using RAM. Physics of Plasmas, 25 (6), 062105.
Sun Z, Li X, Cui G, Yi W, Kong L (2020). Hypersonic Target Detection and Velocity Estimation in Coherent Radar System Based on Scaled Radon Fourier Transform. IEEE Transactions on Vehicular Technology, 69 (6), 6525-6540.
Xuefei X, Gui-sheng L (2014). MPD model for radar echo signal of hypersonic targets. The Journal of Engineering, 2014 (8), 399-406.

The following tables and figure provide an overview of Chinese research activity in the hypersonic target detection cluster.

Table 51. Top Researchers – Target Detection Cluster

Name	Affiliation	Publication Count	Median Citations	H-Index
Liao Guisheng	Xidian University	9	30	8
Kong Lingjiang	University of Electronic Science and Technology of China	6	27	4
Yi Wei	University of Electronic Science and Technology of China	6	14	3
Ji Genlin	Nanjing Normal University	1	242	1
Xu Jia	Shanghai Jiao Tong University	2	131	2

Table 52. Top Research Hubs – Target Detection Cluster

Name	Publication Count	Median Citations	H-Index
Xidian University	27	9	12
University of Electronic Science and Technology of China	13	9	7
Harbin Institute of Technology	12	3	3
Chinese Academy of Sciences	7	13	5
Beihang University	7	7	4

Figure 26. Chinese International Collaborative Intensity – Target Detection Cluster

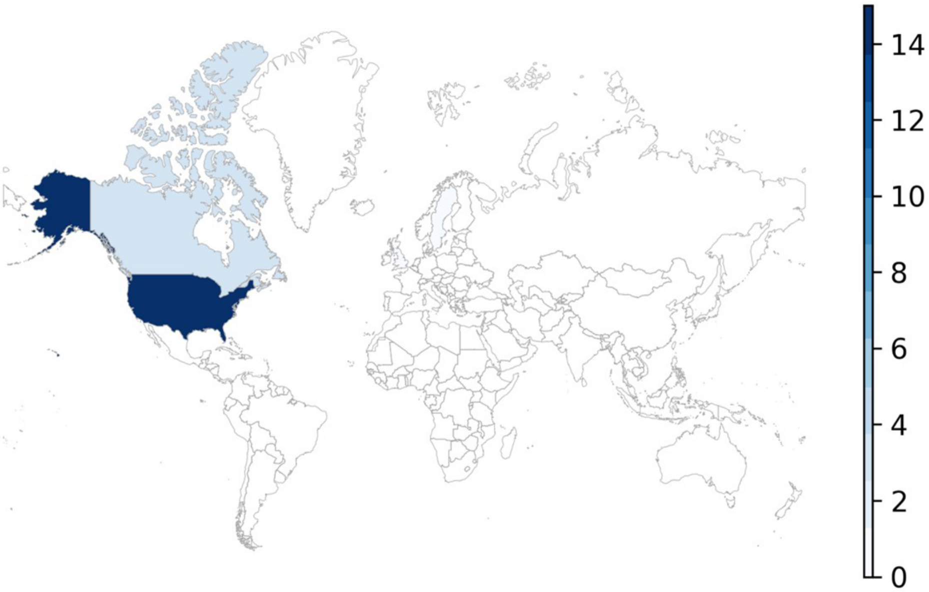


Table 53. Top Five International Collaborators – Target Detection Cluster

Name	Country	Publication Count	Median Citations
University of Delaware	United States	8	25
Shepherd University	United States	1	242
Duke University	United States	2	30
University of Arkansas	United States	2	10
McMaster University	Canada	1	34

Appendix 9: Patent Analysis for Hypersonic Target Detection Group provides a patent analysis for this Group.

Section 3: Notable Rising Researchers and Their Collaboration Networks

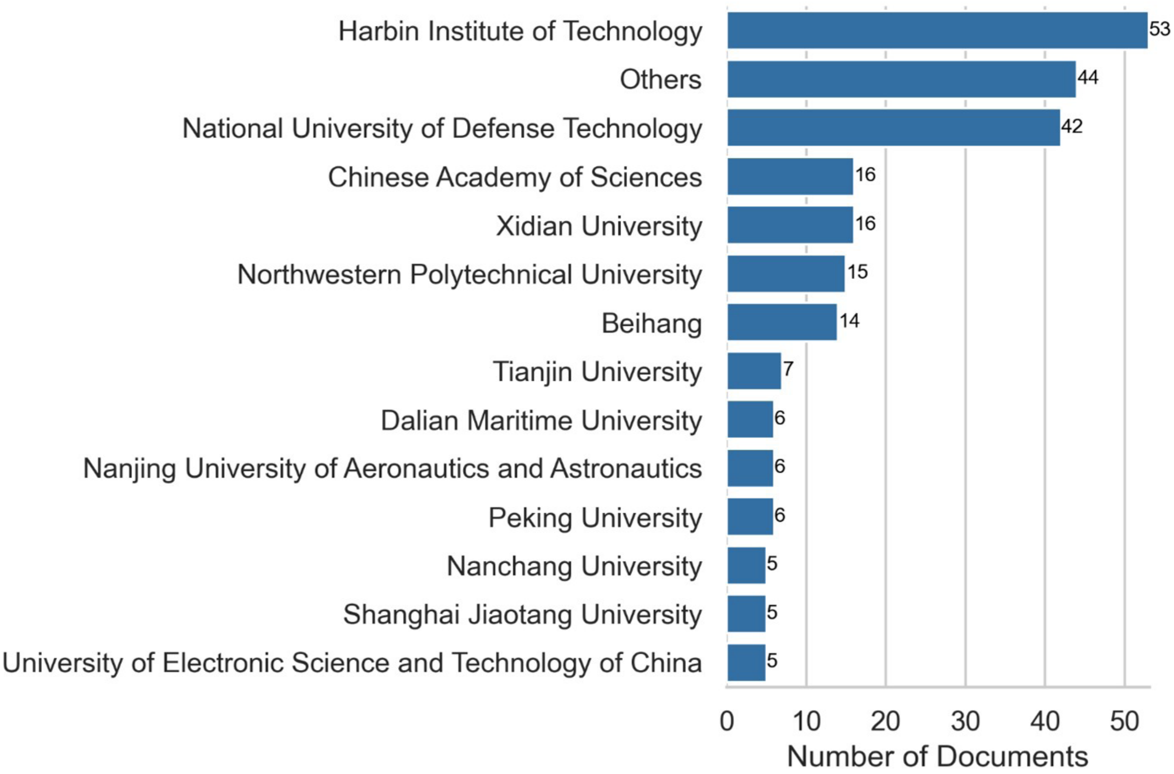
3.1 RISING STARS

This section profiles a group of notable "rising star" researchers who have the potential to lead China's hypersonic and aerospace research for the next decade and beyond. These researchers are currently in their early 40s to 50s, as opposed to some of the preeminent and well-known experts in this field, most of whom are in their late 50s to 60s.

These researchers are selected out of a group of 240 researchers identified by our methodology as "rising stars." This was achieved by first narrowing the list of researchers from our data set to researchers with an initial publication date after the year 2000, then sorting the remaining authors by their first hypersonics publication year and h-index and retaining the top 20 authors.

A number of conclusions can be drawn from an analysis of this dataset. First, Harbin Institute of Technology (HIT) and National University of Defense Technology (NUDT) together account for almost 40 percent of the 240 returns, indicating the instrumental role these two institutions play in cultivating the younger generation of hypersonic and aerospace scientists and engineers.

Figure 27. The Affiliation Makeup of the 240 "Rising Stars" Identified by Our Methodology



Second, in terms of research focus, researchers from HIT publish extensively in a large number of different clusters compared to researchers at other institutions, which appear to have more distinct areas of focus. This was not surprising both given HIT's position as a leading institution for R&D for the PLA and the fact that HIT established a hypersonic technology research center [高超声速技术研究中心] in July 2007 to comprehensively support China's hypersonic and near-space flight vehicle technological development needs. The main research directions of the center cover most major aspects of hypersonic technology, including propulsion systems, materials and thermal protection systems, vehicle integrated design, vehicle control, etc.

Table 54. Hypersonic Technology Research Institution Clusters

Institution	Hits	Clusters
Harbin Institute of Technology	53	• Sodramjet / shock/detonation wave studies • Supersonic aerodynamics and flows • Aerodynamic (s/HS) boundary layers • Combustion in super- and hypersonic engines • Re-entry plasma jet sheath modeling • High-temperature oxidation resistance in ceramics • Thermal shock resistance in ceramics • Adaptive, fault-tolerant control of HVs • Hypersonic target detection
National University of Defense Technology	42	• Supersonic aerodynamics and flows • Aerodynamic (s/HS) boundary layers • Combustion in super- and hyper-sonic engines • Thermal shock resistance in ceramics • Adaptive, fault-tolerant control of HVs
Chinese Academy of Sciences	16	• Thermal shock resistance in ceramics • Wind and/or shock tunnels • Tracking control
Northwestern Polytechnical University	15	• Combustion in super- and hyper-sonic engines • High-temperature oxidation resistance in ceramics • Tracking control • Adaptive, fault tolerant control of HVs
Beihang University	14	• Combustion in super- and hyper-sonic engines • High-temperature oxidation resistance in ceramics • Tracking control • Adaptive, fault-tolerant control of HVs
Tianjin University	7	• Aerodynamic (s/HS) boundary layers • Thermal shock resistance in ceramics • Adaptive, fault-tolerant control of HVs
Dalian Maritime University	6	• Tracking control • Adaptive, fault-tolerant control of HVs

Nanjing University of Aeronautics and Astronautics	6	• Adaptive, fault-tolerant control of HVs
Peking University	6	• Aerodynamic (s/HS) boundary layers • Wind and/or shock tunnels • Tracking control
Nanchang University	5	• Re-entry plasma jet sheath modeling
Shanghai Jiaotong University	5	• Wind and/or shock tunnels • Hypersonic target detection

3.2 NOTABLE “RISING STAR” RESEARCHERS

This section provides brief biographical information about a selected group of notable rising researchers. They are selected to profile because they fit many, if not all, all of the following criteria. An effort was also made to include authors from a variety of institutions.

- A more recent first publication year and a relatively high document count.
- They publish extensively in multiple clusters (four or more).
- They are young (born in the 1970s-1980s).
- Impressive resumes and qualifications.
- They have noted their involvement in PLA-funded key R&D projects.

Notably, although six out of ten researchers have some form of overseas experience—in most cases brief stints under a year—nine out of ten of these researchers completed their undergraduate and graduate course work in China, often receiving their doctorates from the same institutions.18 While speculative, this could indicate a decreasing reliance on foreign programs as pipelines for talent development. This stands in contrast to China’s strategic weapons programs, which for generations relied on scientists who received advanced graduate degrees from foreign institutions.[18]

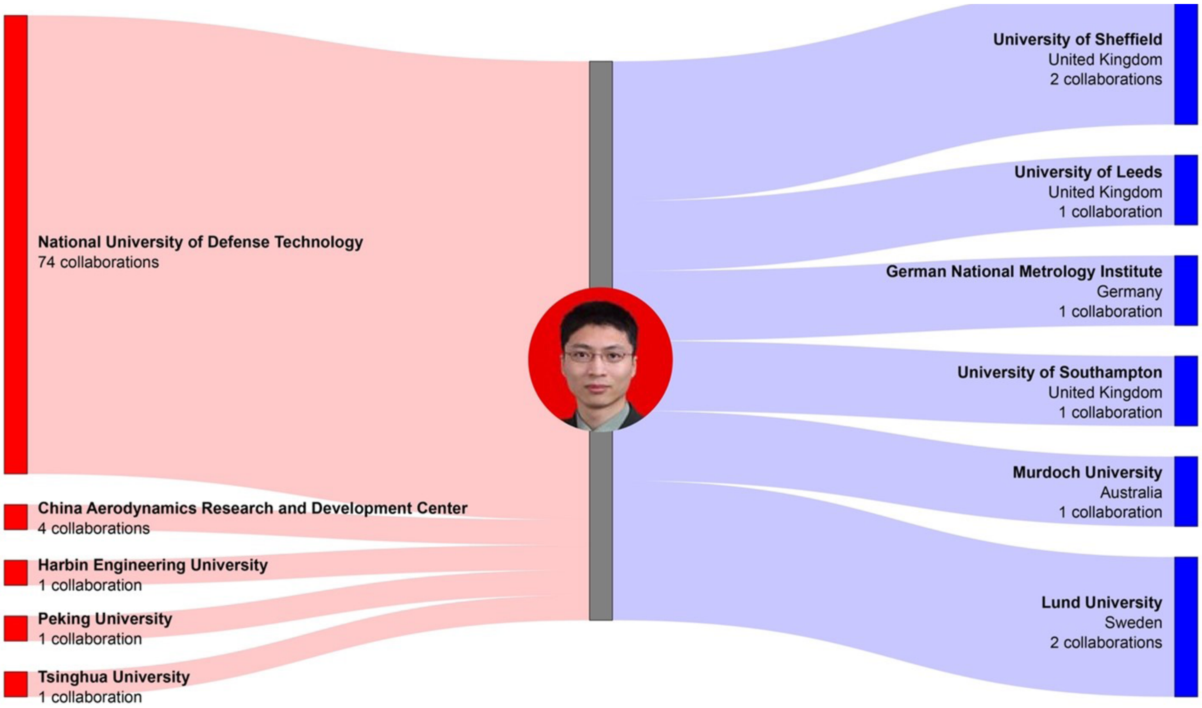
Sun Mingbo [孙明波**]**

Relevant Clusters: Supersonic aerodynamics and flows; Aerodynamic (s/HS) boundary layers; Combustion in super- and hyper-sonic engines

Dr. Sun Mingbo is the director of the Key Lab of Hypersonic Scramjet Engine Technology [国防科大高超声速冲压发动机技术重点实验室主任] at NUDT's College of Aerospace Science and Engineering [空天科学学院]. Born in December 1980 in Henan Province, Sun Mingbo joined the PLA in September 1998. His undated biography on Aminer lists his military rank as Lieutenant Colonel [中校]. Sun's Baidu Scholar and Aminer pages both indicate Sun's close association with his NUDT colleague PLA Major General Wang Zhenguo [王振国], a CAE academician and China's preeminent expert on scramjets and, by far, its most prominent hypersonic weapons expert.

Dr. Sun's stated research interests include supersonic combustion theory, numerical simulation methods, and methods of fuel injection, ignition, flame stabilization and combustion organization in scramjet engines. Sun has published more than 100 journal papers, six monographs, and has 16 authorized patents to his name. His growing academic influence can also be seen in the number of prestigious and highly competitive Chinese national S&T awards he has received. For example, Sun was among a group of ten scholars—and the first scholar ever from NUDT—to receive the China Youth Science and Technology Special Award granted by the China Association for Science and Technology.

Notably, Sun studied in Lund University, Sweden between November 2007 and November 2008. At the 21st AIAA International Space Planes and Hypersonics Technologies Conference held in March 2017 in Xiamen, China, Sun and his NUDT colleagues presented a paper together with Xue-Song Bai, Professor of Fluid Mechanics at Lund University. Sun was also a senior visiting scholar to the University of Southampton, UK between June and November 2015.

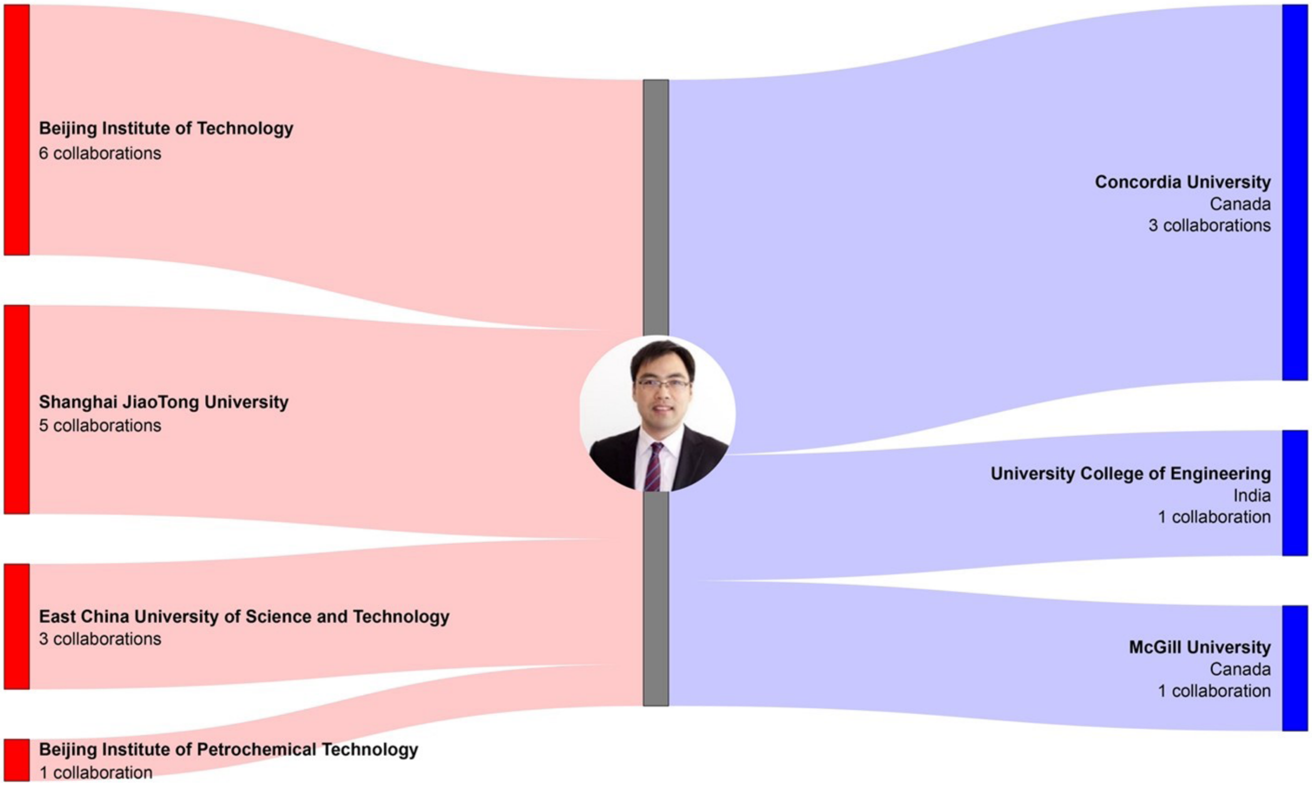


Zhang Bo [张博]

Relevant Cluster: Supersonic aerodynamics and flows

Dr. Zhang Bo is a Researcher[xix] at Shanghai Jiaotong University's[xx] Flight Vehicle Design Department [飞行器设计系], School of Aeronautics and Astronautics [航空航天学院]. His expertise includes shock wave and detonation physics, hypersonic detonation propulsion technology, and explosion and impact dynamics. Notably, Dr. Zhang spent two years (2009-2011) studying in Canada through a joint PhD program administered by the Beijing Institute of Technology[xxi] and McGill University.

Between January 2018 and December 2020, Dr. Zhang was the principal investigator (PI) for a NSFC-funded study looking into the mechanism of turbulence for detonation engines [爆轰发动机]. China reportedly made a breakthrough in the testing of a type of sodramjet in late 2020. It is not yet clear to what extent Zhang's research contributed to this breakthrough or if there is any collaboration between Zhang and the group of scientists from the CAS Institute of Mechanics responsible for the research and development of the sodramjet.



[xix] Researcher [研究员] is a formal title, not simply a job description, which entails a much more dedicated focus on research and lab work as opposed to teaching duties.

[xx] Shanghai JiaoTong University (SJTU) is designated by the Australian Strategic Policy Institute's (ASPI) China Defense University Tracker as "high risk" for its high level in defense research and alleged links to cyber-attacks. See: https://unitracker.aspi.org.au/universities/shanghai-jiaotong-university/.

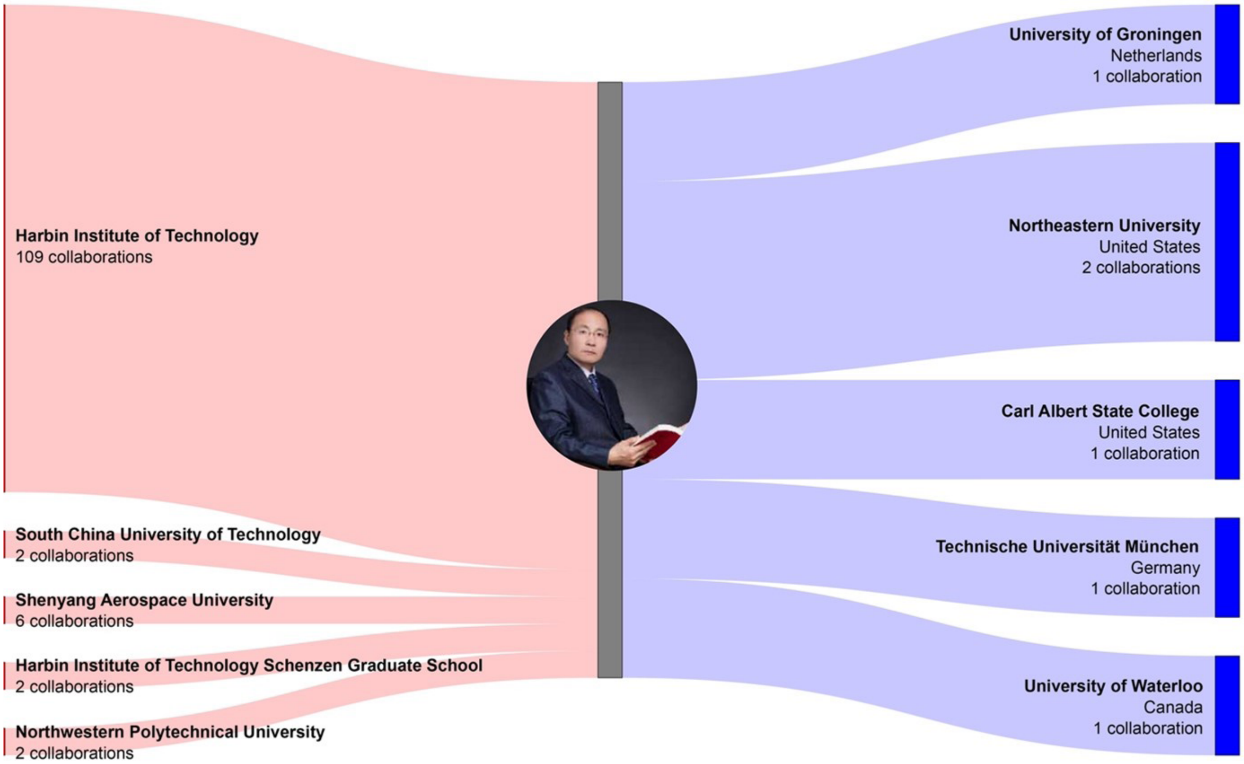
[xxi] Beijing Institute of Technology (BIT) is designated by ASPI's China Defence University Tracker as "very high risk" for its "top-secret security credentials, high number of defence laboratories and defence research areas, and deep involvement in weapons research." See: https://unitracker.aspi.org.au/universities/beijing-institute-of-technology/.

Bao Wen [鲍文]
Relevant Cluster: Sodramjet /shock/detonation wave studies

Dr. Bao Wen, born in 1970, is currently the director of the Hypersonic Technology Research Center of HIT's Academy of Fundamental and Interdisciplinary Sciences [基础与交叉学科研究院] and the deputy director of the Institute of Advanced Propulsion Technology of HIT. Bao completed his undergraduate and graduate coursework at HIT, receiving his doctorate in 1997. According to his personal homepage, Bao is a highly cited author in the aerospace field. In recent years, he has undertaken over 50 research projects funded by the NSFC, the State Administration for Science, Technology and Industry for National Defense (SASTIND), and the Central Military Commision (CMC) S&T Committee, and participated in expert panels for projects related to China's aeroengine megaproject.

According to Bao's personal page, his research team is focusing on the following aspects of hypersonic research between 2020 and 2021:

- The thermal dynamic cycle of and system optimization for Advanced Full Range Engines (AFRE) [先进全速域高超声速发动机热力循环及系统优化研究];
- Intelligent combustion methods for scramjet engines [超燃冲压发动机的智能燃烧组织方法];
- Wireless intelligent field information monitoring method for scramjet engines [超燃冲压发动机的无线智能场信息监测方法].



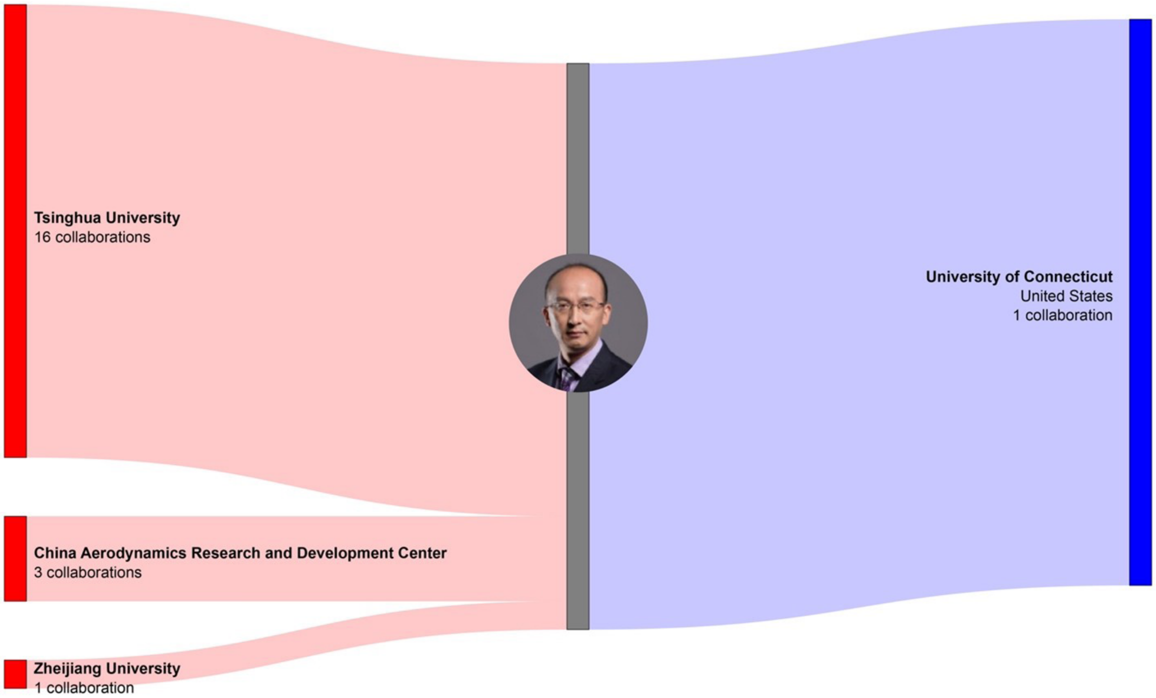
Xiao Zhixiang [肖志祥]

Relevant Cluster: Aerodynamic (s/HS) boundary layers

Dr. Xiao Zhixiang is a Distinguished Research Follow [特别研究员] at the School of Aerospace Engineering [航天航空学院] of Tsinghua University[xxii] and deputy director of the Institute of Flight Vehicle Design [飞行器设计研究所]. He also directs the Laboratory of Aerodynamic Simulation and Design for New Flight Vehicles [新型飞行器气动力仿真与总体设计实验室]. Xiao completed his undergraduate and graduate coursework at NWPU, receiving his doctorate in 2003.

Dr. Xiao has served as the PI for over 100 research projects, most of which specifically oriented at solving critical bottleneck issues with national strategic implications. Xiao's personal page states that he has achieved breakthroughs in technical problems such as hypersonic boundary layer transition, unsteady turbulence simulation, and complex shape aerodynamic thermal simulation, and solved a myriad of difficult problems in the aerodynamic design, flight test, improvement, and modification of a great number of new flight vehicles.

Dr. Xiao has developed extensive ties with China's aerospace and maritime defense industrial establishment, having been contracted by various subsidiaries under Aviation Industry Corporation of China (AVIC), Commercial Aircraft Corporation of China, Ltd. (COMAC), CASC, CASIC, the PLA Navy, and the PLA Air Force, among others.



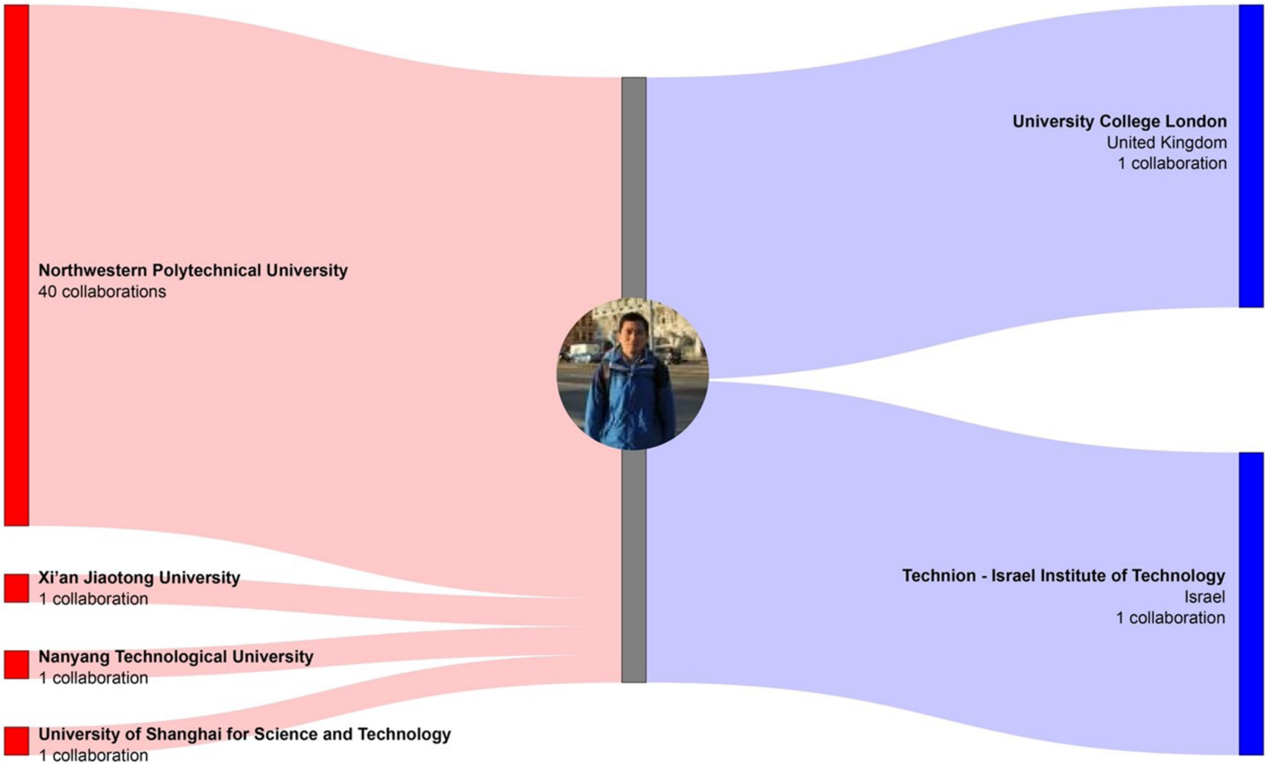
[xxii] Tsinghua University is designated by ASPI's China Defence University Tracker as "very high risk" for its "high level of defence research and alleged involvement in cyber attacks." See: https://unitracker.aspi.org.au/universities/tsinghua-university/.

Qin Fei [秦飞]
Relevant Clusters: Supersonic aerodynamics and flows, Combustion in super- and hypersonic engines

Dr. Qin Fei, born in 1977, is an associate dean [副院长] and professor at the School of Astronautics [航天学院] of Northwestern Polytechnical University.[xxiii] Qin completed his undergraduate and graduate coursework at NWPU, receiving his doctorate in 2008. Between 2014 and 2015, he was a visiting scholar at Lund University in Sweden. He also serves as a Deputy Chief Researcher for the Combustion Chamber for an unidentified type of aerospace combined propulsion engine being developed by CASIC's Third Academy.

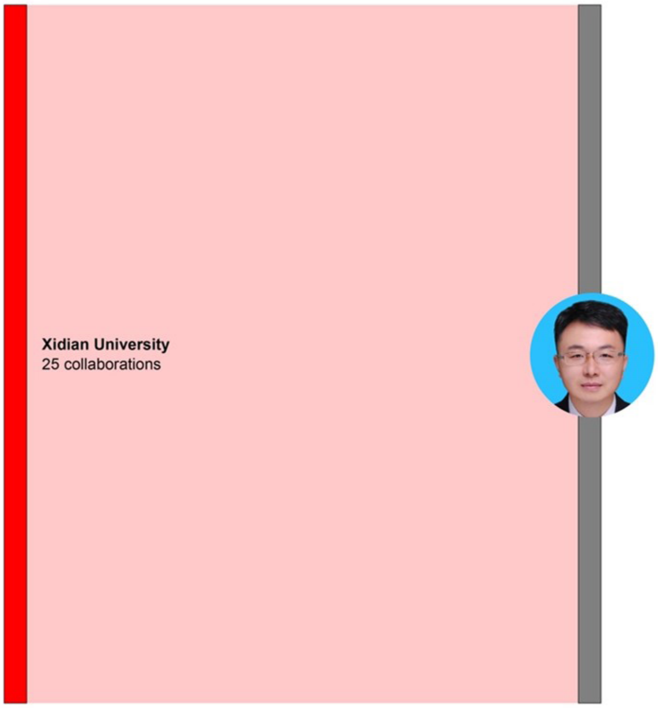
According to his personal webpage, Dr. Qin has long been engaged in the research of rocket engines, air-breathing combined propulsion ramjets, and high-efficiency combustion control, etc. He combines basic research with results-oriented research into high-priority technological areas and have played an instrumental role in the breakthrough of several critical technologies necessary for the development of a new type of combined engine.

Dr. Qin's work has earned him many rewards and accolades, including as a National-Level Defense S&T Expert [国防科技国家级专家], and serving as a member of an unspecified CMC S&T Committee expert panel since 2016.



Shi Lei [石磊]
Relevant Clusters: Re-entry plasma jet sheath modeling

Dr. Shi Lei, born in 1983, is associate dean [副院长] and professor at the School of Aerospace Science and Technology [空间科学与技术学院] of Xidian University. His expertise includes wireless communications, communication technologies for hypersonic vehicles, signal processing and detection and tracking technologies. He is the head of the Research Institute for Aircraft Measurement, Control and Communication [飞行器测控与通信研究所负责人]. Shi completed his undergraduate and graduate coursework at Xidian, receiving his doctorate in 2012. He has been the recipient of multiple research grants from the CMC S&T Committee and SASTIND. Dr. Shi has published more than 30 papers in authoritative journals in the fields of aerospace measurement and control communications, radio wave propagation and plasma physics.



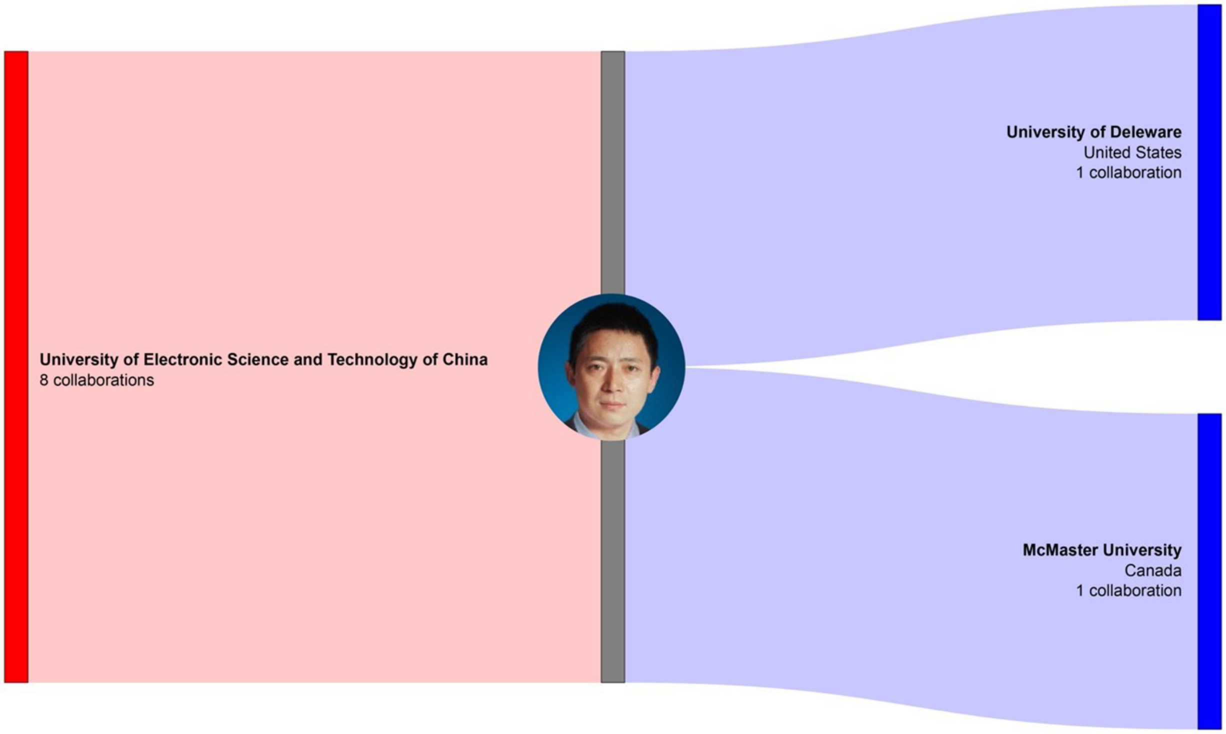
Kong Lingjiang [孔令讲]

Relevant Cluster: Hypersonic target detection

Dr. Kong Lingjiang is Professor and Dean of the University of Electronic Science and Technology of China, School of Information and Communication Engineering [电子科技大学信息与通信工程学院]. He has spent his entire academic career at the University, completing his doctoral degree in 2003 in signal and information processing. He has worked at the University since 2004, other than a brief stint as a visiting scholar at Florida University (2009-2010).

Dr. Kong's research areas include low-observability and weak target detection and tracking technology, broadband radar systems [宽带雷达系统技术], and image processing technology. Other research interests include new system radar [新体制雷达], statistical signal processing [统计信号处理], optimization theory and algorithms [优化理论和算法], radar signal processing [雷达信号处理], and non-cooperative signal processing techniques and adaptive array signal processing [非合作信号处理技术和自适应阵列信号处理].

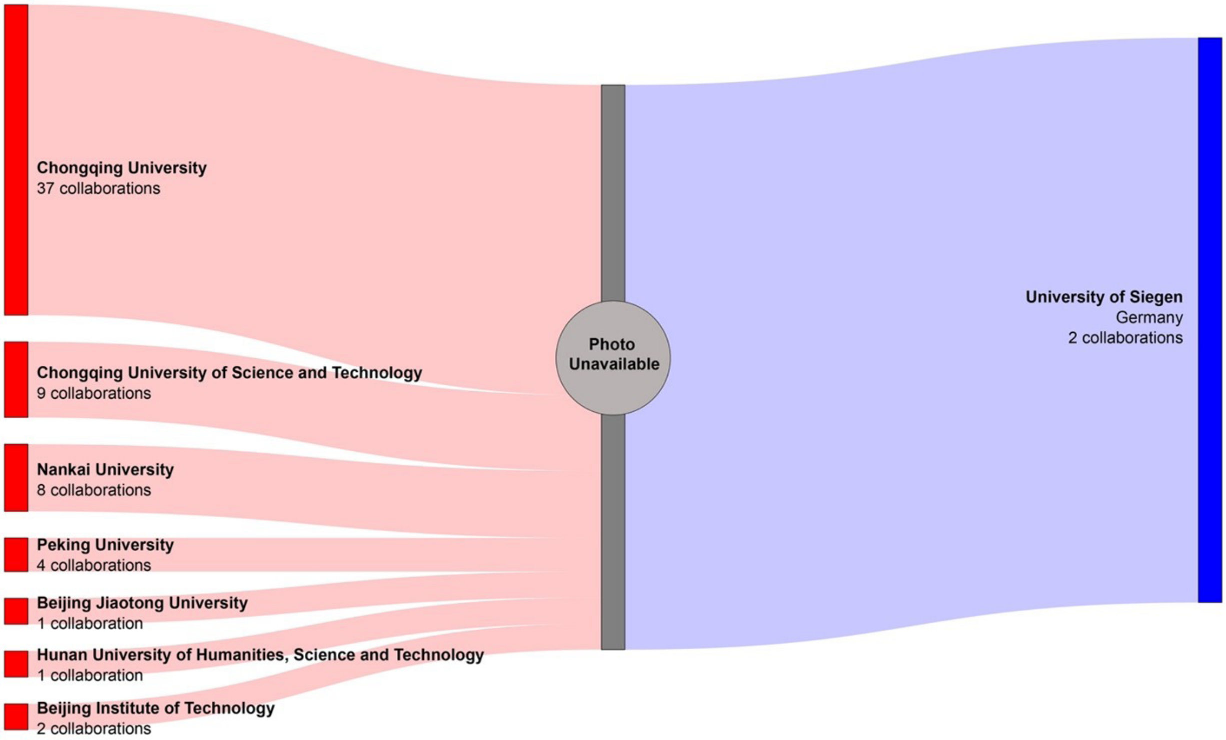
Kong has been a highly productive researcher, having published over 200 journal articles and received authorizations for over 60 patents. He has undertaken a large number of research projects funded by various agencies and pipelines including the national defense pre-research, former PLA General Armaments Department (GAD), NSFC, 863 Program (both civilian and military pipelines), CMC S&T Commission, and CMC Equipment Development Department.



Li Weiguo [李卫国]
Relevant Cluster: Thermal shock resistance in ceramics

Dr. Li Weiguo is a professor at Chongqing University's College of Aerospace Engineering [重庆大学航空航天学院]. Li completed his undergraduate and graduate coursework at Chongqing University, receiving his doctorate in 2005. He went on to post-doc work at Tsinghua University's School of Aerospace [清华大学航天航空学院] in 2008, and then began teaching at Chongqing University's College of Aerospace Engineering, where he has been ever since other than a stint in 2012 as a visiting scholar sponsored by the Chinese government [国家公派访问学者] at Germany's University of Siegen.

Li's main research areas include, among others, thermal protection materials and technologies for hypersonic vehicles and material mechanical behavior testing technology, instrument development and characterization methods in extreme environments [极端环境下材料力学行为测试技术、仪器设备研制及表征方法]. Li has undertaken research projects focusing on heat (and shock) resistance of ultra-high temperature materials [超高温材料抗热], especially ceramics, through two NSFC-funded research programs aimed at advancing hypersonic / near-space flight vehicle technologies.[xxiv]



[xxiv] These include project "research on the high temperature thermal/force coupling characteristics and damage of thermally protected ultra-high temperature ceramics and its mechanism" ["热防护超高温陶瓷的高温热/力耦合特性与破坏及其机理研究"] through NSFC's major research plan [国家自然科学基金重大研究计划] "Key Basic Scientific Issues of Near Space Vehicles" [近空间飞行器的关键基础科学问题] and project "design, preparation and characterization of non-ablative heat-proof mechanisms and materials" ["非烧蚀防热机理与材料的设计、制备和表征"] through NSFC's major research plan "Several Major Basic Issues of Aerospace Vehicles" ["空天飞行器的若干重大基础问题"].

Conclusion

This report took a unique approach to assessing China's HV research strategy and progress using only open source information. We used Cai and Xu's HV development framework as a starting point and then applied machine-learning-enabled analytics to study China's hypersonic research and development activities over time. Our goal was to see what we might be able to learn that would contribute to our overall understanding of China's HV research program.

Evidence that China's HV research activity is aligned with the development framework proposed by Cai and Xu is mixed. First, the largest and most rapidly growing clusters align with Cai and Xu's critical technologies rankings and discussion. Consistent with Cai and Xu's prioritization, the HV program is directing its resources towards C1 (Overall Technology) and especially C2 (Propulsion) while benefiting from the research investments of others in C3 (Materials) and C5 (Flight Navigation, Guidance, and Control). However, the lack of clusters aligning to C4 (Testing and Verification Technology) and C6 (Flight Demonstration and Validation) is inconclusive. This may be due to this research being classified or because these efforts have moved from the research domain to development (where open source data is less available), a hypothesis that is supported by the identification of relevant patents.

China's HV research/field evolved dramatically with a large increase in activity starting around 2016, and focused on Cai and Xu's most critital HV technologies including:

- C2-1 Scramjet engine technology [超燃冲压发动机技术]
- C2-2 Combined propulsion system technology [组合推进系统技]
- C1-1 External design and aerodynamic force numeric simulation technology [外形设计与气动力数值模拟技术]

Patent activity would normally increase as research investment grows, but China's HV patent activity dropped. We suspect that this surprising result is due to China's crackdown on superfelous patent activity in this same timeframe rather than being HV-specific.

The public data also suggests that China's progress is increasingly the result of domestic efforts, rather than international collaboration or scienitsts who have been trained abroad. Our analyses indicated that influential younger scientists only spent minimal time abroad and were only involved in a handful of collaborative projects with interntional instituions and scholars. A likely related trend is that a significant portion of relevant HV work is being done by the Harbin Institute of Technology and the National University of Defense Technology, both of which are key research institutions for the PLA.

This study only represents an initial step toward a more comprehensive understanding of China's HV R&D strategies and progress using open source data. Due to scope and available subject matter expertise, this report focused on only 10 of the 64 clusters identified via quantative analysis. The limitations of purely academic and public data restrict the granularity of the conclusions drawn, and inputs from hypersonic technology SMEs and other data sources would likely lead to additional insights.

APPENDIX 1: BACKGROUND ON HYPERSONIC VEHICLE TECHNOLOGY

This appendix provides more detailed biographies of Cai Guobiao and Xu Dajun.

As of writing, Cai Guobiao is a professor at Beihang University and serves as the Director of Beihang's Aerospace Flight Vehicle Technology Research Institute [空天飞行器技术研究所], an organization created to work on BUAA's interdisciplinary major research projects [学校重大项目跨学院研究所]. He previously served as the managing Deputy Director of the Beihang's School of Astronautics [宇航学院]. He is a national Changjiang Scholar [长江学者] and heads the "Spacecraft Design Optimization and Dynamic Simulation" Key Lab under the Ministry of Education. His research areas include vacuum plumes and their effects, liquid rocket engine multi-disciplinary optimization and simulation techniques, hypersonic flight vehicles, and properties of missile exhaust. He has received many awards including a first-class military S&T award, as well as one first-class and five second-class national defense S&T awards. Two of these citations were for scientific papers he co-authored with Xu Dajun: "Calculation of ablation of thermal protection layer in solid-liquid ramjet combustion chamber" in 2002 and "Numerical Simulation and Experimental Study of Supersonic Combustion" in 2004. Cai was a COSTIND (Commission for Science, Technology and Industry for National Defense; SASTIND's predecessor) Project 511 Scholar, and has served on expert review panels for various national R&D programs, such as China's next generation launch vehicle, manned spaceflight, and satellite systems programs.

Xu Dajun is a lecturer at Beihang University and an expert on airbreathing hypersonic vehicle and launch vehicle design, aerospace design, and ramjet/scramjet technology. Xu received his Ph.D. in spaceflight propulsion theory and engineering from Beihang's School of Astronautics in 2007. From February to May 2012, he was a visiting scholar at the Royal Melbourne Institute of Technology in Australia. Xu has been awarded a first-class military S&T citation and two second-class national defense S&T citations. Xu has also coauthored other books on HVs, including Ramjet Principles and Technology [冲压发动机原理与技术 (2014)], and Solid Ballistic Missile and Launch Vehicle Conceptual Design [固体弹道导弹与运载火箭概念设计 (2018)].

APPENDIX 2: PATENT ANALYSIS FOR OVERALL TECHNOLOGY GROUP

There were 281 patents filed by Chinese inventors from 2012 through 2019. Three patents were filed internationally: one with the United States Patent and Trademark Office (USPTO), and two with the World Intellectual Property Organization (WIPO). The top patent organizations and inventors for the Overall Technology Group are listed below.

Table 55. Top Inventing Organizations

Name	Patent Families	Granted in China	Granted outside China
Nanjing University of Aeronautics and Astronautics (NUAA)	32	19	0
National University of Defense Technology (NUDT)	32	18	0
China Academy of Aerospace Aerodynamics (CAAA)	20	10	0
China Academy of Launch Vehicle Technology (CALT)	19	13	0
Xiamen University	17	13	0

Table 56. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
You Yancheng	Xiamen Xiangteng Aviation Technology Co., Ltd.	18	13	0
Liu Jun	National University of Defense Technology	18	10	0
Li Yiqing	Xiamen Xiangteng Aviation Technology Co., Ltd.	14	12	0
Huang Wei	National University of Defense Technology	14	10	0
Ding Feng	National University of Defense Technology	10	7	0

Representative patents from this Group include:

Design method for variable-Mach-number parallel wide-speed-range waverider aircraft based on osculating-cone theory (CN201710871292)

National University of Defense Technology; Zhao Zhentao; Zhang Tiantian; Huang Wei; Li Langquan; Liao Lei; Li Shibin; Yan Li

First filed 2017-09-22 • First granted 2018-02-09 • Filed in China

The invention provides a design method for a variable-Mach-number parallel wide-speed-range waverider aircraft based on the osculating-cone theory. Firstly, an upper surface trailing edge line and a shock wave outlet molded line of the waverider aircraft are given, then discrete configuration of the Mach number interval is designed, and a datum flow field is generated; and the designed Mach number interval is discretized through a certain discrete law, the discretized Mach number interval is matched with discrete points on the upper surface trailing edge line, and accordingly the discrete points on the upper surface trailing edge line can be subjected to streamline tracing in the datum flow field under the different Mach numbers so as to obtain a lower surface trailing edge line and a leading edge line, and accordingly the waverider aircraft with the variable-Mach-number waverider configuration is designed. According to the variable-Mach-number parallel wide-speed-range waverider aircraft, the defect of poor repeatability and reproducibility in an existing design scheme of a wide-speed-range waverider aircraft is overcome, the limitation that the shock wave surface of a cone-derived waverider aircraft can only be conical is broken through, the requirement for wider flight speed range and airspace is met, and the practicability of the waverider aircraft is further expanded.

Observation method of hypersonic internal flow-field wave structure (CN201710103354)

China Academy of Aerospace Aerodynamics (CAAA); Yuan Minglun; Chen Xing; Sha Xinguo; Ji Feng; Wen Shuai

First filed 2017-02-24 • First granted 2017-05-31 • Filed in China

The invention discloses an observation method of a hypersonic internal flow-field wave structure, particularly a method for obtaining a model internal flow-field wave structure, which is simple, feasible, and low in construction cost. The observation method utilizes theories of glow discharge flow-field display technologies to carry out partial cross-section observation on the model internal flow-field wave structure. In a test, one side of a model is made of a transparent material, so that glow discharge images are shot conveniently; a plurality of discharge electrodes are arranged on internal relative walls of the model, a discharge control unit is adopted for selecting a pair of the electrodes in sequence to discharge, and a synchronous control unit is adopted for synchronizing glow discharge and camera shooting, therefore, flow-field wave structures of multiple sections can be obtained in one test. The method has the advantages of simple structure and relatively low equipment requirements, and is a flow-field display method which can be used in hypersonic low-density wind tunnels.

Integrated aerodynamic layout method for hypersonic aircraft forebody, air inlet duct and supporting plate (CN201610067619)

Nanjing University of Aeronautics and Astronautics; Tian Xuang; Cheng Keming; Yan Lingfeng; Cheng Chuan; Wang Chengpeng; Xue Longsheng; Ni Shiyang

First filed 2016-01-29 • First granted 2016-05-04 • Filed in China

The invention discloses an integrated aerodynamic layout method for a hypersonic aircraft forebody, an air inlet duct and a supporting plate. A combined standard flow field combining an inner core flow field, an isentropic flow field and a truncated Busemann flow field is adopted; a streamline tracer technology is used, based on a free incoming flow capture size and a downstream combustion chamber inlet size given by the overall configuration of an aircraft; a forebody compression face, an air inlet duct compression face and a supporting plate lateral compression face are constructed with traced streamline clusters starting from an outlet of the downstream air inlet duct; and the forebody, the air inlet duct and the supporting plate are smoothly connected to achieve integrated aerodynamic layout configuration. The three-dimensional space structure of the aircraft forebody and the air inlet duct is improved, the disturbing influence of the supporting plate is eliminated in a side face compression mode, adverse factors are converted into favorable compensation, the forebody, the air inlet duct and the supporting plate are reasonably laid out from the space three-dimension perspective, and flowing is kept to be isentropic to the maximum extent, which is beneficial for reducing flowing loss and improving overall performance of the aircraft.

Air-breathing rocket motor and hypersonic speed plane (CN201810529464)

National University of Defense Technology; Ren Chunlei; Zhang Hailong; Fan Xiaoqiang; Yu Jiangfei; Jiang Luxin; Liu Weidong; Liu Shijie

First filed 2018-05-29 • First granted 2018-11-06 • Filed in China

The invention discloses an air-breathing rocket motor and a hypersonic speed plane. The air-breathing rocket motor and the hypersonic speed plane include an air inlet, a heat exchanger, a gas compressor, a main combustion chamber and an exhaust nozzle, and the air inlet, the heat exchanger, the gas compressor, the main combustion chamber and the exhaust nozzle are arranged in sequence. The gas compressor is provided with a turbine, and the turbine provides driving force for the gas compressor. A wall surface cooling channel is arranged on the outer wall surface of the main combustion chamber and the exhaust nozzle. The air-breathing rocket motor and the hypersonic speed plane also include an oxidizing agent pump, a fuel pump, a pre-burning chamber and an injector. The oxidizing agent pump communicates with the heat exchanger so that oxidizing agent enters the heat exchanger to cool air which enters the air inlet. The fuel pump communicates with the wall surface cooling channel, so that fuel enters the wall surface cooling channel to cool the exhaust nozzle and the main combustion chamber. The oxidizing agent after cooling the air and the fuel after cooling the exhaust nozzle and the main combustion chamber correspondingly enter the pre-burning chamber for combustion to generate rich combustion gas in the pre-burning chamber. The injector is used for spraying the air cooled by a heat exchanger and pressurized by a gas compressor into the main combustion chamber for mixed combustion, as well as the rich combustion gas after driving the turbine.

Technology for rapidly calculating ablation effect of complex hypersonic flight vehicle (CN201611056358)

Nanjing University of Aeronautics and Astronautics; Li Jiawei; Wang Jiangfeng; Yang Tianpeng; Wang Yuhan

First filed 2016-11-24 • First granted 2017-05-17 • Filed in China

The invention discloses a technology for rapidly calculating the ablation effect of a complex hypersonic flight vehicle and belongs to the field of aerodynamic design of flight vehicles. The technology adopts an ablation model based on a carbon-based material and a method for calculating the ablation effect based on temperature zone division; combines with non-sticking outflow solution of the Prandtl theory and a boundary-layer theory; develops a technology for rapidly calculating an ablation effect value based on the carbon-based material; gives the heat flux density distribution of surface ablation of a thermal protection system of the complex-appearance hypersonic flight vehicle, the ablation rate and time-variant characteristics of temperature distribution of a thermal protection structure. In addition, the surface ablation situation simulating capability of the thermal protection system is increased in the high-speed flight trajectory process of the hypersonic flight vehicle. The method is high in computational efficiency and good in robustness, results are accurate, the blank that a value simulating result is efficiently, rapidly and accurately given under the situation that a domestic hypersonic flight vehicle produces ablation is filled, and an effective technical support is provided for an initial design stage of the hypersonic flight vehicle.

APPENDIX 3: INTERNATIONAL COLLABORATION: SUPERSONIC AERODYNAMICS AND FLOWS

The quantitative analysis showed limited international collaborations in key HV technologies. However, there was one international collaboration that stood out due to the level of activity, impact, and the subject matter of the research. The researchers highlighted in red in the table below are the key collaborators. Their research collaborations, along with associated citations counts (one indicator of impact), are provided below.

Table 57. Collaborators of HV Technologies

International Researcher	University Affiliation	Country
Ahmad Shafee	Duy Tan University	Vietnam
Nguyen Dang Nam	Duy Tan University	Vietnam
Quyet Van Le	Duy Tan University	Vietnam
Tran Dinh Manh	Duy Tan University	Vietnam
Rasoul Moradi	Khazar University	Azerbaijan
Hossein Moayedi	Ton Duc Thang University	Vietnam
Houman Babazadeh	Ton Duc Thang University	Vietnam
Pouyan Talebizadehsardari	Ton Duc Thang University	Vietnam
Quang-Vu Bach	Ton Duc Thang University	Vietnam
Trung Nguyen-Thoi	Ton Duc Thang University	Vietnam
Truong Khang Nguyen	Ton Duc Thang University	Vietnam

This international collaboration produced the following articles (citiation count is provided as it is an indicator of research impact):

Numerical study on rarefied unsteady jet flow expanding into vacuum using the Gas-Kinetic Unified Algorithm (2017)

Jun-Lin Wu (China Aerodynamics Research and Development Center, National Laboratory for Computational Fluid Dynamics), Zhi-Hui Li (National Laboratory for Computational Fluid Dynamics, China Aerodynamics Research and Development Center), Ao-Ping Peng (China Aerodynamics Research and Development Center), Xing-Cai Pi (China Aerodynamics Research and Development Center), Zhong-Hua Li (China Aerodynamics Research and Development Center)
3 citations

Mixing enhancement mechanism induced by the cascaded fuel injectors in supersonic flows: a numerical study (2018)

Wei Huang (National University of Defense Technology), Yong Li (No Affiliation Given), Li Yan (National University of Defense Technology), Rasoul Moradi (Khazar University)
12 citations

Effect of fuel jet arrangement on the mixing rate inside trapezoidal cavity flame holder at supersonic flow (2019)

Sunwen Du (Taiyuan University of Technology), Abdullah A.A.A. Al-Rashed (The Public Authority for Applied Education and Training), M. Barzegar Gerdroodbary

(Babol Noshirvani University of Technology), Rasoul Moradi (Khazar University), Amin Shahsavar (None), Pouyan Talebizadehsardari (Ton Duc Thang University)
27 citations

The effect of sinusoidal wall on hydrogen jet mixing rate considering supersonic flow (2020)
Zhixiong Li (Minjiang University, University of Wollongong), Tran Dinh Manh (Duy Tan University), Mostafa Barzegar Gerdroodbary (Babol Noshirvani University of Technology), Nguyen Dang Nam (Duy Tan University), Rasoul Moradi (Khazar University), Houman Babazadeh (Ton Duc Thang University)
24 citations

The influence of the sinusoidal shock generator on the mixing rate of multi hydrogen jets at supersonic flow (2020)
Yicheng Li (Jiangsu University), M. Barzegar Gerdroodbary (Babol Noshirvani University of Technology), Rasoul Moradi (Khazar University), Houman Babazadeh (Ton Duc Thang University)
19 citations

Influence of backward-facing step on the mixing efficiency of multi microjets at supersonic flow (2020)
Zhixiong Li (Minjiang University, University of Wollongong), Rasoul Moradi (Khazar University), Seyed Maziar Marashi (Babol Noshirvani University of Technology), Houman Babazadeh (Ton Duc Thang University), Gautam Choubey (No Affiliation Given)
4 citations

Numerical simulation of the hydrogen mixing in downstream of lobe strut at supersonic flow (2020)
Xinglong Liu (Minjiang University), Mohsen Sheikholeslami (Babol Noshirvani University of Technology), M. Barzegar Gerdroodbary (Babol Noshirvani University of Technology), Amin Poozesh (K.N.Toosi University of Technology), Ahmad Shafee (Ton Duc Thang University), Rasoul Moradi (Khazar University), Zhixiong Li (Minjiang University, University of Wollongong)
3 citations

Computational study of the multi hydrogen jets in presence of the upstream step in a Ma=4 supersonic flow (2020)
Xinglong Liu (Minjiang University), Rasoul Moradi (Khazar University), Tran Dinh Manh (Duy Tan University), Gautam Choubey (No Affiliation Given), Zhixiong Li (University of Wollongong, Minjiang University), Quang-Vu Bach (Ton Duc Thang University)
0 citations

Mixing enhancement of multi hydrogen jets through the cavity flameholder with extended pylon (2020)

Zhixiong Li (Minjiang University, University of Wollongong), M. Barzegar Gerdroodbary (Babol Noshirvani University of Technology), Mohsen Sheikholeslami (Babol Noshirvani University of Technology), Ahmad Shafee (Duy Tan University), Houman Babazadeh (Ton Duc Thang University), Rasoul Moradi (Khazar University)
6 citations

The influence of the wedge shock generator on the vortex structure within the trapezoidal cavity at supersonic flow (2020)

Zhixiong Li (Minjiang University, University of Wollongong), Tran Dinh Manh (Duy Tan University), M. Barzegar Gerdroodbary (Babol Noshirvani University of Technology), Nguyen Dang Nam (Duy Tan University), Rasoul Moradi (Khazar University), Houman Babazadeh (Ton Duc Thang University)

20 citations

Numerical experiment on the flow field properties of a blunted body with a counterflowing jet in supersonic flows (2018)

Wei Huang (National University of Defense Technology), Rui-rui Zhang (National University of Defense Technology), Li Yan (National University of Defense Technology), Min Ou (National University of Defense Technology), Rasoul Moradi (Khazar University)

27 citations

APPENDIX 4: PATENT ANALYSIS FOR PROPULSION TECHNOLOGY

There were 321 patents filed by Chinese inventors from 2012 through 2020. Two patents were filed internationally, both with WIPO. The top patent organizations and inventors for the Propulsion Technology Group are listed below.

Table 58. Top Organizations

Name	Patent Families	Granted in China	Granted outside China
National University of Defense Technology	39	25	0
Nanjing University of Aeronautics and Astronautics	34	29	0
Xiamen University	28	21	0
Northwestern Polytechnical University	25	13	0
Nanjing University of Science and Technology	16	12	0

Table 59. Top individual inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
You Yancheng	Xiamen University	27	20	0
Yuan Huacheng	Nanjing University of Aeronautics and Astronautics	11	11	0
Liu Jun	Nanjing University of Aeronautics and Astronautics	11	9	0
Teng Jian	Nanjing University of Aeronautics and Astronautics	10	9	0
Tan Huijun	Nanjing University of Aeronautics and Astronautics	10	9	0

Large-scale hyshot scramjet engine and three-dimensional petal-shaped section combustor (CN201510079040)

National University of Defense Technology; Sun Mingbo; Wang Zhenguo; Tan Jianguo; Liang Jianhan; Zhao Yuxin; Zhao Guoyan

First filed 2015-02-13 • First granted 2015-05-27 • Filed in China, World Intellectual Property Organization (WIPO)

The invention provides a large-scale hyshot scramjet engine and a three-dimensional petal-shaped section combustor. The three-dimensional petal-shaped section combustor comprises a fuel injection section, a flame stabilization section and an expansion section, wherein the wall face of the flame stabilization section is in a lobe structure where bumps and recesses are alternatively formed on the circumference direction; the bumps of the lobe structure gradually approach towards a center axis along a flow direction; the lobe structure extends to the tail end of the fuel injection section, so as to form a petal-shaped structure; a second group of orifices are formed in each of the top points of the bumps at the tail end of the fuel injection section; a first group of orifices are formed in each of the top points of the recesses at the upstreams of the second group of the orifices, so as to form combined injection. According to the three-dimensional petal-shaped section combustor, the lobe structure can divide incoming flow air into a plurality of strands of air flows, so that the injection mixing of fuels is beneficial; bump injection and recess injection of a combustor are combined, so that the effect that the fuels are uniformly mixed in a short distance is realized. Furthermore, no support plates exist in the combustor, so that the thermal protection limit is easy to realize.

Hollow-shaft ram-rotor based on shock wave compression technology (CN201610624343)

Dalian Maritime University; Yang Ling; Han Jiang; Yan Hongming; Zhong Jingjun

First filed 2016-03-04 • First granted 2016-11-09 • Filed in China

The invention discloses a hollow-shaft ram-rotor based on the shock wave compression technology. The hollow-shaft ram-rotor comprises a hollow shaft, a wheel disc assembly assembled with the hollow shaft in a synchronously rotating mode and an outer case arranged outside the wheel disc assembly in a covering mode, wherein a plurality of spiral separating plates are evenly distributed on the surface of the outer wall of the outer edge of a wheel disc of the wheel disc assembly, and the installation angles of all the spiral separating plates are identical; an air inlet flow channel is formed by a gap between every two adjacent spiral separating plates, and each air inlet flow channel is provided with an air flow compression section, a throat separating section and a triangular outlet extension section which are sequentially arranged from the inlet end to the outlet end. Each air flow compression section is a compression air channel with the radial gap being gradually reduced; each throat separating section is an equal-area passage with the radial gap kept unchanged; each triangular outlet extension section is an air channel with the radial gap kept unchanged, and the interior of the peripheral cylindrical surface of each triangular outlet extension section is triangular. According to the hollow-shaft ram-rotor adopting the technical scheme, fluid is compressed by a curved shock wave system, the supercharge ratio is high, and the hollow-shaft ram-rotor is simple and compact in overall structure and high in reliability.

Single-pair supersonic flow direction vortex generation device (CN201811611564)

Nanjing University of Aeronautics and Astronautics; Lin Zhengkang; Lu Shijie; Zhang Kexin; Ma Zhiming; Huang Hexia; Guo Yunjie; Tan Huijun

First filed 2018-12-27 • First granted 2019-04-19 • Filed in China

The invention discloses a single-pair supersonic flow direction vortex generation device. The device comprises a laval nozzle, a transition section, a vortex generation section and a test window which are sequentially connected. A uniform supersonic flow is formed through the laval nozzle and the transition section and enters the vortex generation section; the side wall boundary layer is induced to form transverse flow by means of radial pressure gradient; a pair of large-scale flow direction vortices are generated on one side of a pipeline; and through the design of wave elimination, a uniform and background-free supersonic core flow and a fully-developed single-pair supersonic flow vortex can be generated in the test window. The vortex generation device has the advantages of being simple in structure, convenient to integrate with an existing test bed and display a flow field, and effectively avoiding the pollution of a background wave system to the flow field. In addition, the flow channel area of a test device is gradually increased, and an additional vortex generation device is not needed, so that the requirement of a direct-connected test bed on the plugging degree of a model is more easily met, a feasible test device is provided for researching the interference mechanism of a shock wave string and the supersonic flow direction vortices in a scramjet engine.

Solid rocket ramjet fuel gas flow regulation device driven by linear motor (CN201310380537)

Nanjing University of Science and Technology; Chen Xiong; Zhou Jun; Zhao Zemin

First filed 2013-08-28 • First granted 2013-12-04 • Filed in China

The invention discloses a solid rocket ramjet fuel gas flow regulation device driven by a linear motor. The nozzle throat area of a fuel gas generator is changed through the linear motor driving a cone-shaped valve head, and thus the fuel gas flow of the fuel gas generator is regulated. An inner shell structure is formed in the fuel gas generator; a thermal insulation bushing is mounted in an inner shell; the tubular linear motor is arranged in the thermal insulation bushing; a rotor of the linear motor is fixed in the thermal insulation bushing; a stator of the linear motor is fixedly connected with one end of a valve rod, the other end of the valve rod is fixedly connected with the cone-shaped valve head which stretches into a spray pipe of the solid fuel gas generator, one end, close to the cone-shaped valve head, of the valve rod is matched with an inner hole of the thermal insulation bushing; an annular groove is arranged; a movable sealing piece is arranged in the annular groove; and a pressure sensor is mounted at a rear seal head of the fuel gas generator. According to the solid rocket ramjet fuel gas flow regulation device driven by the linear motor, fuel gas flow can be accurately and randomly regulated, the precision is high, the structure is simple and compact, the size is small, the weight is light, and the sealing effect is reliable.

APPENDIX 5: PATENT ANALYSIS FOR MATERIALS, PROCESSING, AND MANUFACTURING TECHNOLOGY TECHNOLOGY GROUP

There were 122 patents filed by Chinese inventors from 2012 through 2019. Two patents were filed internationally, both with the USPTO. The top patent organizations and inventors for the Materials, Processing, and Manufacturing Technology Group are listed below.

Table 60. Top Inventing Organizations

Name	Patent Families	Granted in China	Granted outside China
National University of Defense Technology	6	6	0
Central South University	3	2	2
China Academy of Launch Vehicle Technology	6	5	0
Aerospace Research Institute of Materials And Processing Technology	5	4	0
Harbin Institute of Technology	5	2	0

Table 61. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
Cheng Jingqing	Wuhu Dingheng Material Technology Co., Ltd.	7	2	0
Zhou Xialiang	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	
Chen Xiaoming	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	
Liu Jun	National University of Defense Technology	4	3	0
Zhao Jian	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	0
Mao Pengzhan	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	

Wu Yanming	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	
Fu Li	Ministry Of Water Resources, Hangzhou Machinery Design Institute	4	3	0

Representative patents from this Group include:

Novel ultrahigh-temperature ceramic integrally-modified anti-ablation carbon/carbon composite material and preparation method thereof (US201815985736)

Central South University; Sun Wei; Xiong Xiang; Chen Zhaoke; Zeng Yi; Wang Dini; Wang Yalei

First filed 2017-05-22 • First granted 2017-08-08 • Filed in China, US

The invention discloses a novel ultrahigh-temperature ceramic (Zr0.8Ti0.2C0.74B0.26) integrally-modified anti-ablation carbon/carbon composite material and a preparation method thereof. The preparation method comprises the following steps: (1) performing high-temperature thermal treatment on a carbon fiber preform, and depositing pyrolytic carbon in a chemical gas phase permeation furnace to prepare a porous carbon/carbon composite material; (2) placing the carbon/carbon composite material on which the pyrolytic carbon is deposited on zirconium-titanium mixed powder, and preparing a zirconium-titanium carbide modified carbon/carbon composite material in a non-stoichiometric ratio through a high-temperature infiltration reaction method; (3) placing the composite material in mixed powder of C, B4C, SiC, Si and a penetration enhancer, and forming an integral ultrahigh-temperature ceramic modified carbon/carbon composite material by adopting an embedding method. The method is simple, is convenient to operate, can be used for preparing large-sized components, and is suitable for integrally modifying substrates and coatings of anti-ablation carbon/carbon composite materials in heat-resistant components of hypersonic aircrafts.

C/C-ZrC composite material as well as preparation method and application thereof (CN201611103115)

National University of Defense Technology; Li Yong; Guo Yimin; Chen Si'an; Ma Xin; Lin Wenqiang; Hu Haifeng

First filed 2016-12-05 • First granted 2017-04-26 • Filed in China

The invention discloses a C/C-ZrC composite material and a preparation method thereof. The C/C-ZrC composite material is prepared by taking a carbon fiber preformed unit as reinforcement and pitch carbon and ZrC as matrixes, wherein pitch carbon is prepared from pitch subjected to catalytic crosslinking, pyrolysis and graphitization, and zirconium carbide is prepared from zirconium poly(acetylacetonate) subjected to catalytic crosslinking and pyrolysis conversion. The preparation method comprises precursor preparation, melt impregnation, catalytic crosslinking, compression semi-coking, pyrolysis, densification, graphitization, re-densification, and other steps. The C/C-ZrC composite material is excellent in high temperature resistance and ablation and scouring resistance, high in ZrC content and consistency, and short in preparation period, thereby being applied to the preparation of a thermal protection material for hypersonic-velocity aircraft.

Cast gamma-TiAl alloy suitable for temperature of 800°C (CN201710305177)

Northwestern Polytechnical University; Hu Rui; Zhang Keren; Yang Jieren

First filed 2017-05-03 • First granted 2017-07-28 • Filed in China

The invention discloses a cast gamma-TiAl alloy suitable for the temperature of 800°C. The cast gamma-TiAl alloy is composed of Al, Nb, Ta, B and Ti, and the cast gamma-TiAl alloy is obtained through an ingot casting smelting manner. By means of the high-Al and medium-Nb cast gamma-TiAl alloy with excessive peritectic solidification used in the temperature of 800°C, it is ensured that the alloy has good oxidation resistance performance and casting performance, meanwhile, the strength of the alloy is improved, and the alloy is suitable for manufacturing aerospace aircraft low-pressure turbine blades, hypersonic aircraft air inlet way wallboards, tank and automobile supercharger turbines and other hot end parts.

Compact pure-phase lanthanum zirconate ceramic with low thermal conductivity and high strength, and preparation method thereof (CN201310730564)

Zhejiang University; Liu Yi; Feng Bin; Hong Zhanglian; Li Xiangxiang

First filed 2013-12-26 • First granted 2014-05-21 • Filed in China

The invention discloses compact pure-phase lanthanum zirconate ceramic with low thermal conductivity and high strength, and a preparation method thereof. The chemical formula of the lanthanum zirconate ceramic is La2Zr2O7, the compactness is greater than 85%, the compression strength is 310-500MPa, the thermal conductivity and the thermal diffusion coefficient at normal temperature respectively are 1.55-1.79W/(m·K) and (0.90-0.76)×10-6m2/s; the thermal conductivity and the thermal diffusion coefficient at the temperature of 1,200°C respectively are 0.75-0.94W/(m·K) and (0.35-0.45)×10-6m2/s; and the breaking tenacity is 1.45-1.70MPa. The lanthanum zirconate ceramic prepared according to the lanthanum zirconate ceramic preparation method provided by the invention has the advantages of low thermal conductivity, high melting point, good inoxidizability, excellent mechanical properties, good high temperature-phase stability and the like, and the requirements of hypersonic velocity aerospace vehicles on the performances of high-strength thermal insulation ceramic materials can be met.

High temperature antioxidative ZrB2-SiB6 superhigh temperature ceramics and preparation method thereof (CN201410010773)

China Academy of Launch Vehicle Technology; Aerospace Research Institute of Materials and Processing Technology; Zhao Yanwei; Li Junping; Wang Zhenbo; Zhou Yanchun; Sun Xin

First filed 2014-01-09 • First granted 2014-06-04 • Filed in China

The invention relates to high temperature antioxidative ZrB2-SiB6 superhigh temperature ceramics and a preparation method thereof, particularly relates to a method for preparing SiB6 particle-reinforced ZrB2 superhigh temperature ceramics by hot-pressing sintering, and a method for improving the antioxidation performance of the composite material, and belongs to the technical field of high temperature ceramics. The ZrB2-SiB6 superhigh temperature ceramics prepared in the invention have excellent performance, such as high melting point, high strength, low modulus, good ablation resistance, and chemical corrosion resistance; have a weight loss ratio of only 0.3 mg/cm2 at air environment of 1,500°C, which is higher than that of pure ZrB2 superhigh temperature ceramics (about 13 mg/cm2) reported at home and abroad; largely meet requirements of practical application of some heatproof structural members; and have wide application prospects in extreme environment of hypersonic speed flight, atmospheric re-entry, trans-atmospheric flight, rocket propulsion system, and the like.

APPENDIX 6: PATENT ANALYSIS FOR TESTING AND VERIFICATION TECHNOLOGY GROUP

There were 167 patents filed by Chinese inventors from 2012 through 2019. None of these patents were filed internationally. The top patent organizations and inventors for the Testing and Verification Technology Group are listed below.

Table 62. Top Inventing Organizations

Name	Patent Families	Granted in China	Granted outside China
China Academy of Aerospace Aerodynamics (CAAA)	28	18	0
Ultra-High-Speed Aerodynamics Institute, China Aerodynamics Research and Development Center	17	11	0
Institute of Mechanics, Chinese Academy of Sciences	16	8	0
Nanjing University of Aeronautics and Astronautics	12	9	0
Beihang University	11	9	0

Table 63. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
Xu Xiaobin	Ultra-High-Speed Aerodynamics Institute, China Aerodynamics Research and Development Center	20	12	0
Zhu Tao	Ultra-High-Speed Aerodynamics Institute, China Aerodynamics Research and Development Center	13	9	0
Lin Jingzhou	Ultra-High-Speed Aerodynamics Institute, China Aerodynamics Research and Development Center	12	9	0

Zhong Jun	Ultra-High-Speed Aerodynamics Institute, China Aerodynamics Research and Development Center	11	7	0
Zhang Xinyu	Institute of Mechanics, Chinese Academy of Sciences	10	4	0

Representative patents from this Group include:

Hypersonic wind tunnel film cooling experiment system and experiment method (CN201611241239)

China Academy of Aerospace Aerodynamics (CAAA); Xiao Weizhong; Xiong Hongliang; Xiang Xingju; Wei Lianfeng; Zhao Xuejun; Wang Hongwei

First filed 2016-12-29 • First granted 2017-05-17 • Filed in China

The invention provides a hypersonic wind tunnel film cooling experiment system and an experiment method. The system comprises a two-dimensional cooling model (1), a film plenum chamber (2), a film spraying pipe (3), an air charging channel (4), a cooling window (5), a particle broadcaster (6) and a cooling medium (7). The front edge of the two-dimensional cooling model (1) is aligned to the lower surface of the outlet of a wind tunnel spraying pipe. The film plenum chamber (2) is installed a surface A, through which the free incoming flow passes, of the two-dimensional cooling model (1), and a reverse step will not be formed after the film plenum chamber is installed. The film spraying pipe (3) is installed on the film plenum chamber (2) and the direction of the central line of a spraying opening is parallel to the surface A. The lower surface of the spraying opening of the film spraying pipe (3) is parallel to the upper surface of the cooling window (5), and reverse step will not be formed therebetween. In an experiment process, the cooling medium (7) enters the film plenum chamber (2) via the air charging channel (4) through the particle broadcaster (6), and then is sprayed out by the film spraying pipe (3), and a cooling shear mixing layer film is formed on the surface of the cooling window (5).

Hypersonic wind tunnel pressure measurement structure (CN201520860355U)

University of Science and Technology Beijing; Yang Haibo; Sun Dongbai; He Ning

First filed 2015-10-30 • First granted 2016-04-13 • Filed in China

The utility model provides a hypersonic wind tunnel pressure measurement structure belongs to the wind-tunnel pressure measurement technical field. This pressure measurement structure includes a conical head, cone and hole. Wherein, conical head and cone are distributed in conical head and the cone to have and are designed good hole by threaded connection, and the hole is circumference and distributes. A pressure sensor arranges the hole in, and the hole size is greater than the pressure sensor size for the pressure measurement. It is tangent with the surface that the hole bottom is arc-shaped. This pressure measurement structure makes things convenient for placing of pressure sensors, acquisition aircraft surface pressure data that can be fine, has a simple structure and is convenient to use.

Process layout method for conventional hypersonic speed wind tunnel (CN201410554961)

Beijing Aerospace Yisen Wind Tunnel Engineering Technology Co Ltd; Shi Yunjun; Sun Yongtang; Cui Chun

First filed 2014-10-17 • First granted 2015-03-25 • Filed in China

The invention discloses a process layout method for a conventional hypersonic speed wind tunnel. The process layout method includes the following steps: a fixed supporting base for bearing axial force of components before a test section of the conventional hypersonic speed wind tunnel is arranged on a heat pipeline before a front chamber, the test section is fixed immovably, and axial force generated by an ultra-expanding section in the bearing test of the fixed supporting base is set; the front chamber can move toward the side of the axis of the conventional hypersonic speed wind tunnel to provide space for replacing a spray pipe; two branches are arranged behind the ultra-expanding section, one branch is provided with an ejector, and the other branch is led to a vacuum container, and the two branches are each provided with a valve used for switching and selecting the branches. Due to the technical scheme, the conventional hypersonic speed wind tunnel can have two operation modes, and the capacity for simulating the flight height of an air vehicle of the conventional hypersonic speed wind tunnel is greatly improved.

Hypersonic wind tunnel experiment module (CN201210584316)

National University of Defense Technology; Wang Zhenguo; Liang Jianhan; Zhou Jin; Yi Shihe; Liu Weidong; Zhou Yongwei

First filed 2012-12-28 • First granted 2013-04-24 • Filed in China

The invention discloses a hypersonic wind tunnel experiment module which comprises an experiment module body. A module door is arranged on the experiment module body. A cross section of the experiment module body along a longitudinal direction is a circle. The module door is an arc-shaped a flap cover which is connected with the experiment module body in a movable mode. When the experiment module door is in a closed state, the center of the cross section arc of the arc-shaped flap cover is in the center line of the experiment module body along the longitudinal direction. Due to the fact that the arc-shaped flap cover is connected with the experiment module body in a movable mode, the opening space of the experiment module body is large when the arc-shaped flap cover is opened, the experiment module body is suitable for large laboratory models getting in and out; and therefore the technical problems that the existing experiment module body is difficult for the large laboratory models to get in and out, labor intensity is large and efficiency of experiments is low are solved. The hypersonic wind tunnel experiment module is large in opening space, capable of facilitating getting in and out of the large experiment models and adjusting space postures of the large experiment models, improving efficiency of wind tunnel experiments and enabling experimental operations of operators to be convenient.

Indirect measuring method for hypersonic speed wind tunnel turbulence scale (CN201410220104)

Xiamen University; Pan Chengjian; Hu Bin; Li Yiqing; Ouyang Zhixian; You Yancheng; Teng Jian

First filed 2014-05-23 • First granted 2014-08-06 • Filed in China

The invention relates to wind tunnel turbulence scale measuring, in particular to an indirect measuring method for hypersonic speed wind tunnel turbulence scale. According to the indirect measuring method for hypersonic speed wind tunnel turbulence scale, a miniature airspeed head is used for measuring pressure pulsation in a hypersonic speed wind tunnel flow field, and then the turbulence scale is indirectly obtained according to relation conversion between pressure pulsation and speed pulsation. The method includes the steps of wind tunnel data collecting and data analyzing. According to wind tunnel data collection process, an adjustable device of the miniature airspeed tube is used for measuring pulsation pressure values at different positions of wind tunnel incoming implement.

APPENDIX 7: PATENT ANALYSIS FOR FLIGHT NAVIGATION, GUIDANCE, AND CONTROL TECHNOLOGY GROUP

Chinese inventors filed 127 relevant patents between 2012 and 2019. None of these patents were filed internationally. The top patent organizations and inventors for the Flight Navigation, Guidance, and Control Technology Group are listed below.

Table 64. Top Inventing Organizations

Name	Patent Families	Granted in China	Granted outside China
Northwestern Polytechnical University	16	13	0
Xidian University	12	10	0
Beihang University	13	8	0
Nanjing University of Aeronautics and Astronautics	15	4	0
National University of Defense Technology	11	7	0

Table 65. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
Xu Bin	Northwestern Polytechnical University	13	12	0
Chen Wanchun	Beihang University	7	4	0
Shi Zhongke	Northwestern Polytechnical University	6	6	0
Shou Yingxin	Northwestern Polytechnical University	5	4	0
Guo Yuyan	Northwestern Polytechnical University	4	4	0

Representative patents from this Group include:

Aircraft neural network learning control method based on lumped composite estimation (CN201810950223)

Northwestern Polytechnical University; Shou Yingxin; Xu Bin

First filed 2018-08-20 • First granted 2018-10-16 • Filed in China

The invention relates to an aircraft neural network learning control method based on lumped composite estimation. Firstly, a longitudinal channel model of an aircraft is decoupled into a speed subsystem and a height subsystem; dynamic inverse control is used for the speed subsystem, and backstepping control is used for the height subsystem; a neural network is used for estimating the dynamic uncertainty of the system, and the coupling from an elastic mode is estimated by a nonlinear observer; a lumped forecast error of two estimations is constructed based on online data, and the forecast erroris applied to updating laws of the neural network and the nonlinear observer; height and velocity controllers are given based on two types of estimator information to achieve the tracking of height and velocity, and finally the control method is applied to the elastic model of the hypersonic aircraft.

Longitudinal guidance method for gliding flight section of hypersonic flight vehicle (CN201510102948)

Beijing Aerospace Automatic Control Research Institute; Qi Zhenqiang; Tang Haihong; Ma Weihua; Bao Weimin; Tian Haitao; Yang Ye; Huang Wanwei; Yu Chunmei

First filed 2015-03-09 • First granted 2015-06-24 • Filed in China

The invention discloses a longitudinal guidance method for the gliding flight section of a hypersonic flight vehicle. The method includes the steps that in the gliding section flight process, a guidance system generates a standard flight path instruction in real time according to navigation parameters; the guidance system provides a preset attack angle acx0 according to the flight speed or Mach in the standard flight path instruction; an additional attack angle instruction Dacx is calculated according to the path instruction and measured values provided by a navigation system; a current actual attack angle acx is acquired through calculation according to the preset attack angle acx0 and the additional attack angle instruction Dacx. By the adoption of the longitudinal guidance method for the gliding flight section of the hypersonic flight vehicle, the dynamic characteristic of drag acceleration tracking control can be effectively improved, the tracking control accuracy of drag acceleration under the dynamic condition is improved, fluctuation of a flight path is restrained, and the adaptability of the guidance system to deviations, uncertain interference and uncertain conditions is enhanced.

Target modal estimation based near-space hypersonic velocity target tracking method (CN201410439348)

University of Electronic Science and Technology of China; Xia Mei; Hao Kaili; Cui Guolong; Yi Wei; Li Xiaolong; Kong Lingjiang; Yang Jianyu; Dong Tianfa; Gou Qingsong

First filed 2014-08-30 • First granted 2014-12-10 • Filed in China

The invention provides a target modal estimation based near-space hypersonic velocity target tracking method, which comprises the steps of: tracking a target by utilizing an interactive multi-model tracking algorithm, estimating a target movement mode dynamically and in real time, judging the target movement mode by counting target characteristics, and finally turning to corresponding single-mode matched tracking based on the estimated target movement mode. Competition among multiple models is avoided, and the problems of low tracking precision and the like caused by complex calculation and great model competition of an existing near-space hypersonic velocity tracking algorithm are solved. The target modal estimation based near-space hypersonic velocity target tracking method is low in calculation amount and high in tracking precision, and effectively improves the integral performance of the tracking system.

Method for predicting skipping trajectory of hypersonic glide warhead in near space (CN201510220893)

Harbin Institute of Technology; Zou Xinguang; Qin Lei; Zhou Di; Li Junlong

First filed 2015-05-04 • First granted 2015-07-15 • Filed in China

The invention relates to an aircraft trajectory predicting method, in particular to a method for predicting a skipping trajectory of a hypersonic glide warhead in near space and belongs to the technical field of target tracking. The method aims to solve the problem that by the adoption of an existing method, the prediction precision of the trajectory of a maneuvering target is low. The method comprises the steps that firstly, a trajectory equation of the hypersonic glide warhead is established; secondly, a Kalman filter tracking the movement curve of the hypersonic glide warhead is designed; thirdly, according to the position, the speed and the acceleration of the hypersonic glide warhead at the tracking end moment and the trajectory equation, the attack angle and the roll angle of the hypersonic glide warhead in fight are estimated, the hypersonic glide warhead in the near space flies by a constant attack angle and a constant roll angle in a subsequent flight time period, recursive calculation for the trajectory at a next moment is conducted through the trajectory equation, and then a trajectory prediction value of the hypersonic glide warhead after a time period is obtained.

Modified variable-structure grid interaction multi-model filtering method for tracking hypersonic-speed target of near space (CN201510220880)

Harbin Institute of Technology; Qin Lei; Zhou Di; Li Junlong

First filed 2015-05-04 • First granted 2015-07-22 • Filed in China

The invention relates to a modified variable-structure grid interaction multi-model filtering method, and provides a modified variable-structure grid interaction multi-model filtering method for tracking a hypersonic-speed target of near space. By the modified variable-structure grid interaction multi-model filtering method for tracking the hypersonic-speed target of the near space, the problem that the existing single-model filtering algorithm, the existing fixed-structure interaction type multi-model algorithm and the traditional variable-structure interaction multi-model algorithm cannot be used for quickly tracking a hypersonic-speed maneuvering target of the near space precisely is solved. According to the technical scheme, the modified variable-structure grid interaction multi-model filtering method for tracking the hypersonic-speed target of the near space comprises the following steps of (1) establishing an inertial reference coordinate system and establishing a state equation of maneuvering movement of the target in the inertial reference coordinate system; (2) using a current statistics model of the maneuvering target as a central model and using constant-speed turning models as a left turning model and a right turning model; (3) determining a measurement model of a target tracking system on the basis of the inertial reference coordinate system; and (4) performing state estimation and error covariance matrix fusion. The modified variable-structure grid interaction multi-model filtering method for tracking the hypersonic-speed target of the near space is used for the field of aircraft.

APPENDIX 8: PATENT ANALYSIS FOR FLIGHT DEMONSTRATION AND VALIDATION TECHNOLOGY GROUP

There were 19 patents filed by Chinese inventors from 2012 through 2019. None of these patents were filed internationally. The top patent organizations and inventors for the Flight Demonstration and Validation Technology Group are listed below.

Table 66. Top Inventing Organizations

Name	Patent Families	Granted in China	Granted outside China
Beijing Kongtian Technology Research Institute	3	1	0
No.11 Research Institute of No.6 Academy of China Aerospace Science & Technology Group Corporation	2	2	0
Xi'an Aircraft Design Institute / AVIC First Aircraft Design Institute / 603rd Research Institute	2	2	0
Beihang University	1	1	0
Nanjing University of Aeronautics and Astronautics	1	0	0
Harbin Institute of Technology	1	0	0
Computational Aerodynamics Institute of China Aerodynamics Research and Development Center	1	0	0
Shenzhen Baichuan Rongchuang Technology Co., Ltd.	1	0	0
China Academy of Launch Vehicle Technology	1	0	0
Avic Aerospace Life-Support Industries Ltd.	1	0	0
Hubei Institute of Aerospacecraft	1	0	0
Deepmag Technology (Shenzhen) Co., Ltd.	1	0	0

Table 67. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
Liu Sha	Xi’an Aircraft Design Institute / AVIC First Aircraft Design Institute / 603rd Research Institute	2	2	0
Fan Genmin	China Aerospace	2	2	0
Huyan Xiao	CASC 6th Academy 11th RI	2	2	0
Yong Xuejun	CASC 6th Academy 11th RI	2	2	0
Yang Baoe	CASC 6th Academy 11th RI	2	2	0
Liang Junlong	CASC 6th Academy 11th RI	2	2	0
Zhang Lei	Xi’an Aircraft Design Institute/AVIC First Aircraft Design Institute/ 603rd Research Institute	2	2	0
Zhu Xiangdong	CASC 6th Academy 11th RI	2	2	0
Wang Yufeng	CASC 6th Academy 11th RI	2	2	0
Shi Bo	CASC 6th Academy 11th RI	2	2	0
Guo Bin	CASC 6th Academy 11th RI	2	2	0
Wu Baoyuan	CASC 6th Academy 11th RI	2	2	0
Liu Hua	CASC 6th Academy 11th RI	2	2	0
Zhang Qi	Xi’an Aircraft Design Institute / AVIC First Aircraft Design Institute / 603rd Research Institute	2	2	0

Representative patents from this Group include:

Time-scale separation aircraft elastomer robust control method based on nominal information (CN201810124027)

Xi’an Aircraft Design Institute / AVIC First Aircraft Design Institute / 603rd Research Institute; Zhang Qi; Liu Sha; Zhang Lei

First filed 2018-02-07 • First granted 2018-08-17 • Filed in China

The invention discloses a time-scale separation aircraft elastomer robust control method based on nominal information and belongs to the field of aircraft control. The method is used for solving a control problem that a slow-changing time scale has uncertain time-varying information in existing elastic hypersonic vehicle rigid-flexible mode separation control. The method comprises a step of defining a fast and slow time-scale coupling form of an object dynamics model and completing time and scale separation based on a singular perturbation algorithm to separate a rigid mode from an elastic mode in the dynamic model; a step of designing a robust control strategy based on the nominal information for a slow-changing time scale part characterizing a system rigid mode, completing compensation control through estimating an upper bound of the uncertain time-varying information and realizing high-instruction tracking; a step of designing a sliding mode control strategy for a fast-changing timescale part characterizing a system elastic mode to realize the elastic mode suppression; and a step of combining two control inputs into one to be an overall rudder bias to achieve the effective control of aircraft height and elastic mode.

Separation mechanism applicable to hypersonic speed air inlet duct protection cover (CN201710437431)

Beijing Kongtian Technology Research Institute; Li Xinya; Wang Lei; Zhu Guoxiang

First filed 2017-06-09 • First granted 2018-07-20 • Filed in China

The invention provides a separation mechanism applicable to a hypersonic speed air inlet duct protection cover. The separation mechanism comprises an aircraft precursor and the air inlet duct protection cover. On the premise of meeting the requirement for structural strength, the interior of the aircraft precursor is hollowed out to form a cavity; the aircraft precursor is further provided with a square hole; the air inlet duct protection cover is provided with an unlocking hook which can stretch into the cavity through the square hole; a rotary sliding rod is further arranged in the cavity and used for locking the unlocking hook before unlocking, one end of the sliding rod is a restrained end, the other end is a free end; a tension spring fixed to the wall face of the cavity is connected to one side of the free end, and the tension spring is in a tensioned state when the sliding rod locks the unlocking hook. The other side of the free end is connected with a fiber fusing device. By means of the separation mechanism, the problem that an explosive bolt separation mechanism way cannot be used for a wind tunnel shrinkage model is solved, and the ability of a hypersonic speed wing tunnel carrying out air inlet duct protection cover dynamic separation testing is improved.

Time mark separation aircraft elastomer control method based on nonlinear information (CN201810124039)

Xi’an Aircraft Design Institute / AVIC First Aircraft Design Institute / 603rd Research Institute; Zhang Qi; Liu Sha; Zhang Lei

First filed 2018-02-07 • First granted 2018-07-20 • Filed in China

The invention discloses a time mark separation aircraft elastomer control method based on nonlinear information, belongs to the field of aircraft control, is especially suitable for a hypersonic-velocity aircraft elastomer, and is used for solving the problem that a conventional elastomer hypersonic-velocity aircraft cannot achieve the rigid-flexible mode separation control. The method comprises the following steps: carrying out the kinetic analysis of a hypersonic-velocity aircraft elastomer kinetic model, and clearly determining the coupling mode of rigid-flexible modes; carrying out the quick-slow time-mark decomposition of the model through the singular perturbation theory, and enabling a rigid mode and a flexible mode in the kinetic model to be separated; designing a control strategy based on the linear information for a slow variable time mark part for representing the rigid mode of the system, and enabling a nonlinear item obtained after model decomposition to be directly substituted into a controller; designing a sliding-mode control strategy for a quick variable time mark part for representing the flexible mode of the system; finally integrating the two types of control input into one type of control input as the general rudder deviation, thereby achieving the effective control of the rigid-flexible modes of an aircraft.

Blocking cover actuating device for ramjet separation test (CN201320780600U)

No.11 Research Institute of No.6 Academy of China Aerospace Science & Technology Group Corporation (CASC); Guo Bin; Liang Junlong; Wang Yufeng; Yong Xuejun; Liu Hua; Wu Baoyuan; Yang Bao'e; Fan Genmin; Zhu Xiangdong; Huyan Xiao; Shi Bo

First filed 2013-11-29 • First granted 2014-05-28 • Filed in China

The utility model relates to a blocking cover actuating device for a ramjet separation test. The blocking cover actuating device comprises a cylinder control unit, a blocking cover connecting rod unit and a blocking cover position detection unit and is used for simulating a dynamic process that an air intake duct radome is opened when a ramjet separation transfer test is carried out on a free jet bench. The blocking cover actuating device of the air intake duct test is installed between a jet pipe and an air intake duct lip, and the air intake duct lip is shielded by the blocking cover before separation; and when the separation starts, the blocking cover is opened by an actuating system, the air intake duct begins to capture incoming flow, and pressure is started to be built for channels in the engine. The process of starting pressure buildup in the air intake duct during the ground separation transfer test is ensured to be consistent with a flight test process by the test blocking cover, and authenticity of the ground separation transfer process is ensured; and according to the blocking cover actuating device, the risk that test equipment and the engine are possibly destroyed when the air intake duct radome for the flight test is opened is eliminated.

APPENDIX 9: PATENT ANALYSIS FOR HYPERSONIC TARGET DETECTION GROUP

There were 20 patents filed by Chinese inventors from 2012 through 2020. None of these patents were filed internationally.

Table 68. Top Organizations

Name	Patent Families	Granted in China	Granted outside China
PLA Naval Aeronautical University	7	5	0
Xidian University	3	2	0
Huazhong University of Science & Technology	2	2	0
Northwestern Polytechnical University	2	2	0
Zhejiang University	1	1	0
Harbin Institute of Technology	1	0	0

Table 69. Top Individual Inventors

Name	Affiliation	Patent Families	Granted in China	Granted outside China
Yu Hongbo	Naval Aeronautical and Astronautical University	7	5	0
Wang Guohong	Naval Aeronautical and Astronautical University	7	5	0
Wu Wei	Naval Aeronautical and Astronautical University	5	5	0
Tan Shuncheng	Naval Aeronautical and Astronautical University	4	4	0
Zhang Xiangyu	Naval Aeronautical and Astronautical University	3	1	0

Representative patents from this Group include:

Analysis method of handover conditions of hypersonic-velocity target interception missile based on interception geometry (CN201611049726)

Harbin Institute of Technology; He Fenghua; Ma Jie; Chen Songlin; Yang Baoqing; Wu Jingchuan; Huo Xin
First filed 2016-11-24 • First granted 2017-03-22 • Filed in China

The invention provides an analysis method of handover conditions of a hypersonic-velocity target interception missile based on interception geometry and belongs to the field of aircraft manufacturing technology. The method is technically characterized in that by considering all possible velocity directions of a target and according to the relative motion relation between the interception missile and the target, positions of all possible impact points are obtained through derivation, and the interception geometry is built; according to the research results of the interception geometry and the positional relation among the interception missile at the midcourse and terminal guidance handover moment, the target and the interception geometry and interception conditions required to be met for intercepting the hypersonic-velocity target are given; on the basis that the interception conditions are met, a calculation method of the positional condition and the solving process of the angle condition of the interception missile at the midcourse and terminal guidance handover moment are given, and the influence of maneuvering of the target on solving the angle condition of the interception missile is analyzed. Through the method, the problem that the hypersonic-velocity target cannot be intercepted through an existing interception method is solved.

Hypersonic velocity target TBD detection method for polynomial Hough conversion (CN201610524075)

PLA Naval Aeronautical and Astronautical University; Tan Shuncheng; Wu Wei; Wang Guohong; Yu Hongbo

First filed 2016-07-04 • First granted 2016-08-31 • Filed in China

Aiming at the problem of signal accumulation detection of a hypersonic velocity maneuvering target in a near space in a radar scanning period, the invention discloses a hypersonic velocity target track before detect (TBD) detection method for polynomial Hough conversion, and aims to search movement of a matching target in a radial dimension by using polynomial with velocity and acceleration as parameters, associate by using orientation wave gates in a direction, map the energy on a target track to a parameter space for polynomial Hough conversion, and detect by comparing the maximum energy value of the parameter space with a constant false alarm threshold. According to the method disclosed by the invention, the problem of two-dimensional parameter searching is degraded to the problems of one-dimensional distance search and small-range association in orientation by setting the orientation wave gates, the order times of polynomial search are reduced by setting range gates, and thus the calculation quantity is greatly reduced; meanwhile, in addition to functions of a conventional Hough conversion TBD method, the method disclosed by the invention is also applicable to signal accumulation detection under conditions of strong target movement, fuzzy distance measurement, multiple targets and the like.

Multi-model oval Hough transformation accumulation detection method for invisible ski-jump maneuvering target (CN201410163729)

PLA Naval Aeronautical and Astronautical University; Yu Hongbo; Wu Wei; Tan Shuncheng; Sun Dianxing; Zhang Xiangyu; Wang Guohong; Jiang Hui

First filed 2014-04-16 • First granted 2014-07-30 • Filed in China

The invention discloses a multi-model oval Hough transformation accumulation detection method for an invisible ski-jump maneuvering target. Firstly, the target is detected on a three-dimensional measurement horizontal projection plane by means of Hough transformation, then signal accumulation of the maneuvering target is achieved through the oval Hough transformation in a vertical plane, weight fusion is carried out on multiple oval models due to the fact that target tracks are unknown, so that real tracks in near space are estimated, and accordingly the hypersonic speed invisible maneuvering target in near space can be detected and tracked. According to the method, three-dimensional space maneuvering of the target in near space is converted to linear motions on the horizontal surface and rushing and pressing ski-jump motions in the vertical surface, accumulation detection of the target is achieved through a TBD technique that Hough transformations of the multiple oval models are mutually fused, and compared with common oval Hough transformation, the method can obviously reduce calculation amount, storage amount and complexity due to the fact that subspace searching in a small range is carried out, and is suitable for being applied to projects.

Hypersonic speed target detecting method for polynomial Radon-polynomial Fourier transform (CN201610147273)

PLA Naval Aeronautical and Astronautical University; Tan Shuncheng; Wu Wei; Wang Guohong; Yu Hongbo
First filed 2016-03-15 • First granted 2016-06-08 • Filed in China

The invention relates to a hypersonic speed target detecting method for polynomial Radon-polynomial Fourier transform, and belongs to the technical field of radar signal processing and detecting. The method comprises the steps that N (a certain number) periodic signals to be accumulated are sampled, a slow time-fast time target observed value is extracted, and pulse compression is performed on the sampled signals separately; initialization parameters of polynomial Radon-polynomial Fourier transform are determined; search, compensation and accumulation are performed in a parameter space through polynomial Radon-polynomial Fourier transform to obtain a range-Doppler distribution diagram subjected to phase-coherent accumulation; and constant false-alarm detection and target motion parameter estimation are performed on the range-Doppler distribution diagram. According to the method, model building is performed on target motion through polynomial, range walk and Doppler spread of the signals are compensated through parameter search of the polynomial, and therefore effective accumulation detection on a high-speed high-mobility target can be achieved under a low signal-to-noise ratio background; in addition, effective search on the multi-dimensional parameter space is achieved in a multi-resolution search mode, and therefore the search real-time performance is improved.

Hypersonic speed platform-borne radar clutter generating system and method (CN201410106243)

Xidian University; Xie Rong; Yin Yue; Bian Jiang; Cao Yunhe; Liu Zheng
First filed 2014-03-20 • First granted 2014-06-18 • Filed in China

The invention relates to a hypersonic speed platform-borne radar clutter generating system and method. The system comprises an initializing module, a numbering module, a host end and a distance ring division module of a distance ring parameter calculation module, a scattering unit clutter calculation module, a scattering unit clutter summing module, a distance ring clutter calculation module and a graphic processing unit of the distance ring clutter summing module. The method includes the steps that first, initialization is conducted; second, distance rings are numbered; third, the areas and the angles of the distance rings are acquired; fourth, the distance rings are divided into scattering units; fifth, clutters of the scattering units are calculated; sixth, the clutters of the scattering units are summed; seventh, the clutters of the distance rings are calculated; eighth, the clutters of the distance rings are summed. According to the system and method, the clutters of all the scattering units are calculated in parallel through the GPU, row guiding vectors and column guiding vectors of a foresight planar array are separately processed, the earth surface is treated as the curved surface, and the hypersonic speed platform-borne radar clutter generating system and method have the advantage of generating hypersonic speed platform-borne radar clutters quickly, stably and realistically.

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