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## Research and Validation of System Mechanics Problems in Extreme Environments (Postprint)

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**Date:** 2017-02-08T00:00:00+00:00

### Abstract

Mechanics constitutes the foundation of engineering technology. The remarkable achievements of the 20th century in aerospace, atomic energy utilization, and large-scale mechanical equipment exemplify the successful integration of mechanics with engineering technology. Presently, the discipline of mechanics has progressed from classical mechanics through applied mechanics and technical science to a new stage of system mechanics. Numerous major engineering demands of humanity urgently necessitate the development of novel theories and methodologies in system mechanics. The Special Project for Research and Verification of System Mechanics Problems in Extreme Environments aims to, via typical cases of major engineering projects and complex media systems—including hypersonic cruise flight, long-term safe service of high-speed trains, and efficient separation and transport of deep-sea oil and gas—adopting the research paradigm of system mechanics, elucidate the mechanical principles governing their operation and service in extreme environments, propose systematic solutions, achieve breakthroughs in critical technologies such as load spectrum component prediction and system optimization for hypersonic cruise flight and high-speed trains, as well as efficient separation and transport of deep-sea oil, gas, and water, and conduct experimental verification. Concurrently, addressing frontier scientific issues in international complex media system mechanics, it will investigate coupling mechanisms across multi-phase, multi-field, multi-scale, and multi-process phenomena, develop new theories of system mechanics, guide the developmental trajectory of the mechanics discipline, and consolidate a research team dedicated to system mechanics.

### Full Text

Strategic Priority Research Programs (Category B) of the Chinese Academy of Sciences

ChinaXiv Partner Journal: System Mechanics Problems in Extreme Environments—Research and Validation

Mechanics is the foundation of engineering technology. The outstanding achievements of the 20th century in aerospace, nuclear energy utilization, and large-scale mechanical equipment represent typical cases of the integration between mechanics and engineering technology. These achievements are difficult to realize, posing new challenges to the mechanics discipline while also providing rare development opportunities.

Currently, the mechanics discipline has evolved from classical mechanics through applied mechanics and technical science to a new stage of system mechanics. Numerous major engineering demands urgently require the development of new theories and methods in system mechanics. The System Mechanics Problems in Extreme Environments—Research and Validation Program intends to reveal the mechanical principles of operation and service in extreme environments and propose systematic solutions through typical cases such as hypersonic cruise flight, long-term safe service of high-speed trains, and efficient deep-sea oil-gas separation and transport, following the research approach of system mechanics.

Reviewing the development of mechanics, it has a history of over 300 years since Newton. According to the evolutionary characteristics of disciplinary frontiers, it can be roughly divided into four stages: classical mechanics, applied mechanics, technical science, and system mechanics. The classical mechanics stage lasted approximately 200 years, during which the theoretical framework of mechanics developed significantly and provided a fundamental paradigm for modern scientific development. In the early 20th century, marked by boundary layer theory, applied mechanics emerged, characterized by the organic combination of mechanics with major engineering projects.

In the mid-20th century, with the development of aerospace engineering and the nuclear industry, classical mechanics was no longer sufficient as the theoretical foundation for engineering technology. Scientists at the forefront of mechanics research at that time, such as Qian Xuesen, keenly perceived this and promoted the transition of mechanics toward technical science through interdisciplinary integration and application, consolidating a system mechanics research team.

## 1. Project Background and Rationale

In strategic domains such as aerospace, transportation, and energy, increasingly urgent national needs—including aerospace security assurance, long-term safe service of high-speed trains, and deep-sea oil and gas resource development—all involve the feasibility, safety, and economy of major engineering systems in extreme environments. These issues require extending the research object of mechanics from relatively familiar individual components or component types in conventional environments to engineering systems in extreme environments. The latter typically involves numerous interacting and constraining factors, and extreme environmental test conditions are often difficult to realize, posing new challenges to mechanics while also providing rare development opportunities.

Compared with traditional reductionism in natural sciences, the system me-

chanics research methodology emphasizes the transition from single-factor to multi-factor, from local to global, and from decoupled or weakly coupled to strongly coupled approaches, stressing the integration of mechanical principles with the demands of major engineering systems. The core problems at the level of major engineering and complex media systems lie in clarifying the mechanical principles at the system level and the feasibility of technical routes, examining the important influencing factors of safety, reliability, and economy during system operation or service, their coupling laws and quantitative relationships, and on this basis, dedicating efforts to exploring and discovering transformative technical approaches and overall optimization solutions.

The development of system mechanics requires cultivating and nurturing innovation points across broad research fields. Therefore, this program targets typical major engineering systems such as hypersonic cruise flight, long-term safe service of high-speed trains, and efficient deep-sea oil and gas extraction. These systems are characterized by system-level complexity, multi-factor coupling, extreme service environments, as well as the multi-scale, multi-field coupling, and multi-disciplinary integration features of complex systems at the forefront of mechanics research. The program establishes frontier basic research topics in emerging technology and strategic domains to develop new ideas, theories, and methods at the system level, which is of great significance for solving fundamental theoretical problems of major engineering systems and advancing the mechanics discipline.

The program has assembled a large group of talented young researchers with solid research foundations and outstanding capabilities. The core team comprises over 130 members, including 4 academicians, 13 recipients of the National Science Fund for Distinguished Young Scholars (杰青), 14 recipients of the CAS Hundred Talents Program (百人), 2 recipients of the Young Thousand Talents Program (青千), and 4 recipients of the National Science Fund for Excellent Young Scholars (优青). The core team includes 67 key members under 40 years old, accounting for approximately 50% of the total. The team encompasses outstanding research strengths in multiple disciplines including mechanics, chemistry, materials, mathematics, and computing, with complementary advantages. Additionally, 4 senior academicians have been engaged as academic advisors.

Participating institutions include the Shanghai Institute of Ceramics, Institute of Chemistry, Academy of Mathematics and Systems Science, Computer Network Information Center, and Institute of Engineering Thermophysics of the Chinese Academy of Sciences. These units have long-term research accumulations in their respective fields, first-class software and hardware facilities, and can ensure the smooth implementation of the program.

## 2. Program Structure

The program comprises four projects (Figure 1 [Figure 1: see original paper]): Project I: New Approaches to Hypersonic Cruise Flight and Experimental Val-

idation; Project II: Safety and Reliability of Long-Term High-Speed Train Service; Project III: Efficient Deep-Sea Oil-Gas-Water Separation and Transport Technology; and Project IV: Frontier and Interdisciplinary Mechanics of Complex Media Systems.

These four projects, through research on typical cases, focus on developing original basic theories of system mechanics. They will prioritize breakthroughs in systematic theoretical problems and key technologies for major demands such as hypersonic cruise flight, safety and reliability of long-term high-speed train service, and efficient deep-sea oil-gas-water separation and transport in extreme engineering environments. Additionally, they will cultivate new growth points for system mechanics in areas such as health and bionics, energy and environment, and ship safety.

### 3. Scientific Problems and Key Technologies to be Addressed

The program will adopt a system mechanics perspective, using major demands as examples to establish intrinsic relationships between core technical requirements at the system level and main influencing factors. It will analyze difficulties in previous research and reasons why existing technologies cannot achieve breakthroughs, propose new systematic solutions, and form landmark research achievements through experimental validation. While addressing national major demands, the program will also explore new theories and methods of system mechanics.

In hypersonic cruise flight research, the focus will be on establishing new theories of hypersonic cruise flight, breaking through the hypersonic barrier, and forming integrated hypersonic cruise vehicle technology. In high-speed train long-term service safety research, the focus will be on establishing theoretical prediction methods for unsteady load spectrum components, the coupling relationships between aerodynamic loads and subgrade, wheel-rail, car body, pantograph-catenary systems, and component load spectrum and life prediction methods. In deep-sea oil-gas-water efficient separation and transport technology research, the focus will be on establishing multi-phase strong swirling flow stability theory and control methods, breaking through key technologies of axial swirling and radial separation under deep-sea conditions, and deep-sea long-distance oil and gas transport technology. Additionally, for complex media systems, the focus will be on revealing the multi-phase flow and multi-process coupling laws and intrinsic mechanisms of different hierarchical structures in complex media, non-equilibrium effects of flow and heat transfer under extreme conditions and fluid-structure coupling behavior, the correlation mechanisms between microstructure evolution and macroscopic mechanical response of multi-level structural materials in complex service environments, nano-micro flow mechanisms and transport laws in complex media, and cross-scale theoretical characterization and microstructure origins of advanced materials from discrete to continuous transition.

#### 4. Expected Outcomes

The program is expected to achieve the following results in original theory, key technologies, and talent development:

**Original Theories:** Hypersonic cruise flight theory; unsteady load spectrum component prediction methods; multi-phase strong swirling flow stability and control methods; multi-factor multi-process nonlinear coupling theory for complex media systems; cross-spatiotemporal scale mechanics theories and methods.

**Key Technologies:** Integrated design technology for hypersonic cruise vehicles; high-speed train load spectrum distribution prediction technology; deep-sea oil-gas-water efficient separation technology; integrated structural and functional design technology for impact-resistant materials. Based on the optimal-velocity rocket hypersonic cruise flight scheme, the program will develop a practically viable rocket hypersonic cruise prototype and conduct flight test validation. For high-speed trains, system optimization schemes and life extension solutions will be used for critical component improvements of CRH380 trains and validated through tests on the Beijing-Guangzhou line. For deep-sea applications, design schemes for underwater oil-gas-water separation systems, metering systems, and visual monitoring systems will be developed, and deep-sea simulation environment tests will be conducted for pipeline-type efficient oil-gas-water separation systems and downhole separators.

**Discipline Development and Talent:** The program will explore and develop concepts, theories, and methods of system mechanics, consolidate the system mechanics research team, and cultivate high-end research talent in frontier and interdisciplinary areas of system mechanics: several internationally influential academic leaders, 4-6 recipients of the National Science Fund for Distinguished Young Scholars or Excellent Young Scholars, and over 100 outstanding graduate students. The program will publish over 200 high-level journal papers, apply for more than 20 invention patents, obtain 2-3 software copyrights, and publish 2-3 monographs. It will form an internationally distinctive system mechanics research center.

(Host Institution: Institute of Mechanics, Chinese Academy of Sciences)

*Note: Figure translations are in progress. See original paper for figures.*

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