Development and Prospect of Intelligent Technology for Air-Breathing Engines *

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Abstract: Intelligent technology plays a key role in the future development of air-breathing engines. It can greatly improve the efficiency and performance of air-breathing engines, which reflects the level of research and development of a country's high-end equipment. This paper aims at discussing the research progress of intelligent technology in air-breathing engines. Existing problems and technical challenges in air-breathing engines are analyzed from six aspects: intelligent design, intelligent components, intelligent perception, intelligent control, intelligent self-healing and intelligent maintenance. Finally, some suggestions and prospects are given for future development in several key directions.

Key words: Air-breathing engine; Intelligent technology; Development; Prospect; Review

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吸气式发动机智能化技术发展及展望

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摘 要：智能化技术是支撑未来吸气式发动机发展的重要技术手段，体现了一个国家高端装备的研发水平，可大幅度提高吸气式发动机的研发效率和质量。本文论述了智能化技术在吸气式发动机领域的研究现状，从智能设计、智能部件、智能感知、智能控制、智能自愈、智能维护六个维度分析了吸气式发动机存在的问题及技术挑战，给出了几个重点方向的发展建议及展望。

关键词：吸气式发动机；智能化技术；发展；展望；综述

1 Introduction

As the aircraft engine integrates top technologies in various industrial categories, its design and development have always embodied the most advanced designs, tools and theories. Since the 21st century, the improvement of computing ability has given birth to the application of artificial intelligence technology in various industrial fields and has also caused profound changes in the design of air-breathing engines.

Under the traction of multi-level requirements of the future aircraft, such as fast and long-distance flight, intelligent sensing coordination and flexible maintenance, higher requirements are put forward for the research and development speed, high thrust and low fuel consumption performance, working speed range, ceiling capacity, reliability and maintainability of the air-breathing engines. The application of new ma-

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terials, new methods and new means in the air-breathing engine through intelligent means will be the key to improve the engine capability in the future. In the future, air-breathing engine technology will show an accelerated development trend in the direction of higher thrust-weight ratio, higher reliability, lower fuel consumption, lower cost and maintenance-free. Intelligent engines will be inevitable in future military and civilian air-breathing engines.

According to the requirements of the future aircraft for power plant, the engine capability improvement can be considered from six dimensions: design means, component capability improvement, perception, control, reliability and maintainability. Through intelligent design means and intelligent engine architecture, the research and development speed of engine can be improved. The engine components are changed from traditional components to advanced wide-range adjustable components with 'self-sensing and self-learning' capabilities, which realizes the wide-range active adjustment of the compressor, combustion chamber, turbine and inlet, and provides a means for the intelligent control of the system. The engine sensing technology changes from traditional internal small-dimensional point sensing to multi-dimensional and multi-information fusion intelligent sensing mode including battlefield situation, which provides support for intelligent decision-making, control and self-sensing components under changeable flight missions. The engine control has developed from the traditional off-line control planning mode to the evolutionary learning control mode of on-line sequential planning, achieving the best engine performance. Engine self-healing has changed from 'traditional hardware redundancy and passive fault tolerance mode' to 'model and data-driven active fault tolerance mode', which improves the reliability and realizes engine fault work and dispatch. Based on the existing monitoring and isolation technology of health management, intelligent maintenance is transformed into big data intelligent monitoring, cluster integrated maintenance, robot group monitoring and self-maintenance, which can improve attendance and reduce manual maintenance.

This paper discusses the research progress of intelligent technology in the field of air-breathing engines from six aspects: intelligent design, intelligent components, intelligent perception, intelligent control, intelligent self-healing, and intelligent maintenance. The current problems and technical challenges on air-breathing engines are analyzed, and some suggestions and prospects for several key directions are given.

2 Development of intelligent technology in air-breathing engines

2.1 Research progress of intelligent design in air-breathing engines

Intelligent design refers to the application of modern information technology to improve the intelligence level of computers, so that computers can undertake more and better complex tasks in the design process and become an important auxiliary tool for designers. As a typical representative of intelligent design means, 'Digital Twin' has greatly improved the working efficiency of engine design and attracted the attention of major international aviation powers.

Relying on digital technology, more design processes of engines can be realized in the computer. Specifically, first, modules of different levels, disciplines, and problems are integrated into the engine simulation system. Then use sensors to collect data accumulated in the stages of production, testing, use, and maintenance, and continuously update the engine model. Finally, a digital model that can reflect the different characteristics of the engine system in a complete, efficient, and multi-angle manner is obtained. Such digital technology is called the 'Digital Twin'[1]. The conceptual diagram is shown in Fig. 1.

As a typical representative of intelligent design methods, digital twin has greatly improved the efficiency of engine design, and attracted the attention of major aviation countries in the world.

Under the concept of digital twin, Rolls-Royce company in the United Kingdom launched the 'R^2 Digital Laboratory' program, which aims to establish a high-precision intelligent engine digital twin. GE company in the United States launched the 'Predix' program, which aims to build the industrial internet including the engines[2]. NASA has also promoted the 'Numerical Propulsion System Simulation' research, which purposes to develop a numerical simulation platform that

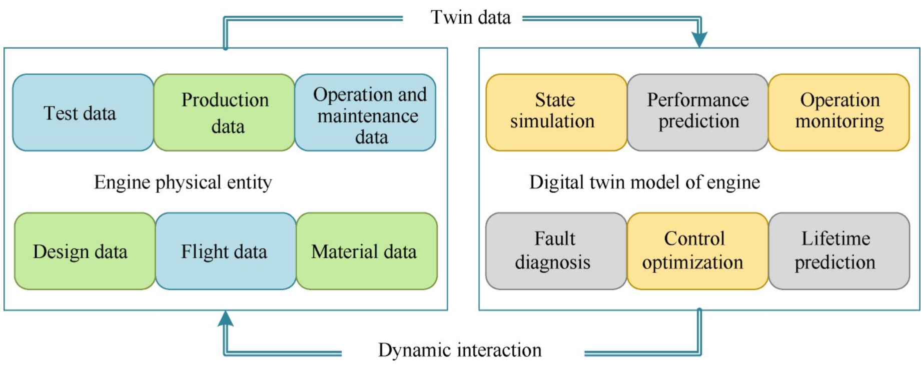

Fig. 1　Conceptual diagram of engine digital twin

can satisfy multiple requirements including engine ensemble design, evaluation and optimization. This simulation can make designers, who are from various disciplines, realize data interaction, scaling, and analysis through the specific interface of the platform during the whole life cycle of air-breathing engine[3-4]. Ghorbani H et al.[5] presented a new methodology to construct an accurate damage-free digital twin model of the defective blades, which can be effectively applied to repair volume generation in remanufacturing, and the robustness of this method was proved in experiments.

China has also made some progress in the field of intelligent design based on digital twinning. Based on the internationally recognized engine system performance modeling methods, relevant domestic institutions and universities have developed engine ensemble/component performance simulation technologies and tools with their own characteristics. For example, under the idea of multi-disciplinary cross and data scaling, Beihang Aircraft Engine Numerical Simulation Research Center has developed the China aircraft engine numerical simulation system, which has functions such as the rapid establishment of engine simulation models and variable-dimensional data scaling[6-7]. Xiong M et al.[8] studied the predictive maintenance framework of aeroengine driven by digital twin and mined the implicit digital twin model. They combined the data drive of deep learning method with Long Short-Term Memory (LSTM) model and applied it to aeroengine, which proved the effectiveness of this method.

2.2　Research progress of intelligent components in air-breathing engines

Compared with traditional engines, the intelligent components of air-breathing engines can improve the performance of the engine by adopting more advanced adjustment methods, which have never appeared or been widely used in traditional engines, such as core engine driven fan with high flux and large flow regulation capacity, adjustable area high pressure turbine guide, deformable air inlet, pneumatic vector nozzle, and modular components with decoupling matching interface, etc. Compared with the transmission engine components, the intelligent components have the ability of local autonomous perception and active control. Active control technology is helpful to improve the operation flexibility of components, so that they can be self-adaptive adjusted under extremely harsh conditions. Thus, it is not necessary to reduce the performance of the engine in all cases for individual cases. Typical cases of active control technology include active inlet control, active stall control, active clearance control, active combustion control, etc.

Since the 1990s, scholars in the world have started to study the distributed control method for aircraft engine and made many beneficial attempts on the intelligent components. Sanders et al. and Song G et al.[9-10] have studied the new intelligent materials with economy and developed an engine inlet adjusting device and an adjustable tail nozzle device made of shape memory alloy (SMA) materials. A feedback controller based sliding-mode method is used to regulate the SMA actuator position and the performance improvement of the engine system is demonstrated. Li Wei[11] from Nanjing University of Aeronautics and Astronautics adopted TMS320F2812 digital signal processor of Texas Instruments (TI) company as microcontroller to design intelligent actuator based on CAN bus, including vector nozzle, rotary metering valve and guide vane controller. Jia Binghui et al.[12] developed a tip clearance sensor using fiber-optic technology for active clearance control of high pressure turbine. Freeman et al.[13] carried out a series of active stall control experiments on a Rolls-Royce Viper turbojet. The results demonstrate that stall control is feasible and can increase the stable operating range by up to 25% of pressure rise. Chen Xianghui[14] studied the preliminary design of the contraction and expansion airfoil of high-pressure turbine for adaptive cycle engine, and compared the effects of different contraction and expansion ratios on the internal flow field. Bai Wei et al.[15] of China Aviation Engine Group analyzed the influence mechanism of nozzle area ratio on vector characteristics by numerical simulation. Through the special tests of the whole machine on the ground and high altitude platform, the data of thrust performance, deflection thrust loss, deflection efficiency and engine matching characteristics under different nozzle area ratios were obtained, which provided important data support for the engineering application of pneumatic vector nozzle. Active combustion control is also one of the important research directions in the field of intelligent components. By optimizing the relationship between a measured reference signal from the sensor and the actuation signal, the unstable heat perturbations and acoustic disturbance can be prevented from coupling with each other[16]. Relying on more advanced dynamic actuators (such as plasma, synthetic jets, swirling jets), the noise can be minimized and the combustion system can be stabilized to avoid structural damage and costly mission failure. In 2009, American Institute of Aeronautics and Astronautics (AIAA) listed the active flow control technology represented by plasma excitation as the fifth of ten frontier technologies in aerospace. Professor Li Yinghong's team[17] in China has also done a lot of research on plasma-driven flow control and combustion control.

With the progress of new materials and other technologies, aero-engine components will increasingly show the characteristics of light weight, high efficiency, electrification, high performance regulation, matching decoupling, etc. Components with these characteristics will be able to support the development of intelligent engines in the future.

2.3 Research progress on intelligent perception in air-breathing engines

As a way to obtain environmental information, intelligent perception is the basis for intelligent systems to learn, judge and make decisions. The essence of intelligent perception is the combination of sensing technology and artificial intelligence. The application of artificial intelligence technology can perceive deeper information through combining, reasoning, and judging multiple characteristic information.

Intelligent perception needs to accomplish three major tasks: signal perception, processing and transmission. In addition, it has to perform functions such as self-checking, redundancy management, fault diagnosis and fault tolerance[18-20], as shown in Fig. 2.

For signal perception, the sensor can use micro-electro-mechanical-system (MEMS)[21] and optical technology[22] to achieve sensing in harsh working environments, or use silicon integrated technology complementary metal oxide semiconductor (CMOS)[23] to arrange multiple sensing units in an array[24]. It can distribute multiple sensitive elements in sensing modules to improve accuracy and reliability through data fu-

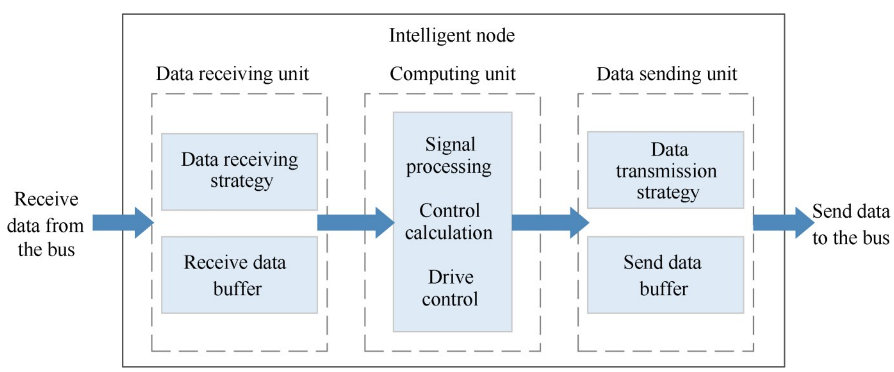

Fig. 2 Architecture model of distributed intelligent devices

sion[25]. For signal processing[26], compared with the traditional sensing method, which uses a single signal to obtain the to-be-measured data, intelligent perception can synthesize multiple physical to-be-measured data[27]. At the same time, by using filtering algorithms, the interference in the signal can be suppressed[28]. Intelligent perception can also use artificial intelligence algorithms to perform self-diagnosis, self-correction and self-compensation for its own offset error, gain error, nonlinear error and other effects[29]. For signal transmission, based on the general communication standard of intelligent sensors, wired or wireless communication can be realized through CAN bus[30] or Zig Bee bus[31].

Intelligentization of perception improves its own detection ability and broadens the breadth. With the help of multi-source information fusion technology, the value of measured parameters can be fully tapped and the depth of perception can be increased. In the field of intelligent perception on air-breathing engines, many deep learning algorithms such as deep belief networks[32-34], automatic encoder[35-37] and convolutional neural networks[38] have been used to process a large amount of flight data. Zhang Shiying et al.[39-40]designed an intelligent temperature sensor based on AVR and intelligent pressure sensor with back propagation (BP) neural network, which played an important role in preventing compressor surge and maintaining engine control stability boundary. Based on these studies, the running state of pneumatic components[41], rotors and bearings in air-breathing engines can be evaluated and predicted. Physical quantities of air-breathing engines that were difficult to be directly measured in the past, such as engine thrust[42], combustion chamber parameters and their field distribution[43], can also be estimated online to some extent through multi-source data obtained in real time.

2.4 Research progress of intelligent control in air-breathing engines

In 1965, the concept of intelligent control was first proposed by a Chinese - American Professor, Fu Jingsun. After 1970, the development of computer technology and the proposal of fuzzy control and expert systems promoted the progress of intelligent control and decision-making research.

Compared with classic control and modern control theories, intelligent control has a greater degree of adaptation to complex environment and tasks. That makes it more suitable for solving the problems of inaccurate engine mathematical models, including multiple control variables, complex structure, strong nonlinearity and uncertainty of external environment[44].

In 2003, the United States proposed the Versatile Affordable Advanced Turbine Engines (VAATE) plan to conduct a research on intelligent propulsion technology. As an important content, advanced control and health management are studied to increase the component efficiency by using active and distributed control methods. At present, the air-breathing engines in developed countries have evolved to the fourth-generation Full Authority Digital Engine Control (FADEC) control system, i.e., intelligent distributed control system. It has been successfully applied to the fifth-generation aircraft engine represented by F135[45].

The research on intelligent control in China started a little later, but has a good development trend, and many important results have been achieved. Wang Yuan et al.[46] proposed a decentralized migration optimization method, which has a stronger ability to get rid of the local optimum problem in the minimum fuel consumption and minimum turbine temperature modes. In the aspect of adaptive control, Guo Yingqing.[47] studied the application of neural network adaptive control in engine and clarified the structure and principle. In the aspect of model predictive control, Xiao Lingfei et al.[48] proposed a nonlinear model predictive control method for turboshaft engines. In terms of life extension control, the Chinese research groups have also conducted many in-depth research. The thermo-mechanical fatigue life of the engine turbine guide vane has been considered and the acceleration control law has been optimized[49-50].

2.5 Research progress of intelligent self-healing in air-breathing engines

'Self-healing' is one of the important features of intelligent air-breathing engines in the future. It mainly focuses on the improvement of reliability and dispatch, aiming at the traditional passive fault tolerance mode of 'hardware redundancy', and changes to the active quality self-healing mode based on 'model and data drive'.

Intelligent self-healing is a kind of anthropomorphic concept that imitates biological self-healing system, including immune system, stress system and repair system. It makes the engine have certain self-reorganization and self-fault tolerance capabilities when facing faults, and it can prevent the engine from falling into 'sub-health state'.

At present, there are two main research directions of intelligent self-healing. One is the self-healing of control and accessory system based on data, which applies more advanced intelligent technology to ensure that the engine can still maintain the performance quality in case of failure. The other is the self-repair of the engine body structure, including the robot technology using self-repair materials and self-inspection and repair. At present, the first kind of technology is widely studied at home and abroad.

For multiple faults of engine control, the intelligent self-healing system can automatically tolerate or deal against[51]. For the 'sub-health' state, such as engine performance degradation and abnormal quality, the intelligent self-healing system can ensure the best engine performance.

The earliest idea of 'intelligent self-healing' for engine control and accessory system stems from the design requirements of robustness and fault tolerance. In the 1980s, American scientific research institutions launched a series of studies on fault detection, isolation and containment of engine control system. NASA Levis Research Center successfully verified the advanced fault detection, isolation and containment technologies of the F100 engine[52]. At the same time, NASA presided over the analytical redundancy technology plan for engine reliability improvement[53]. In the following decades, the self-healing control has been well developed and improved .Gao Jinji[54], an academician from Beijing University of Chemical Technology, has also done in-depth research on intelligent self-healing. He proposed artificial self-healing and artificial intelligence cyber-physical system (CPS) three-body model, and proposed intelligent self-healing technology of vibration fault monitoring based on high-quality data acquisition and data-driven intelligent diagnosis, aiming at the vibration problem of aero-engine, and put forward the development goals and suggestions of intelligent vibration fault monitoring of aero-engine in the future.

At present, the intelligent level of self-healing control for advanced engines in aviation powers is not high. Only the single electronic and electrical fault can be dealt with. Moreover, in China, the related research is still in the infant stage. The existing models still cannot achieve complete self-healing for single or paired electronic and electrical faults, which is far behind developed countries.

2.6 Research progress of intelligent maintenance in air-breathing engines

Intelligent maintenance system refers to a new type of maintenance system, which uses performance degradation analysis and prediction method[55], combined with Internet, contactless communication and embedded intelligent electronic technologies, to enable equipments with self-organization and self-learning ability[56] and achieve zero fault nearly[57].

The development of fault diagnosis and maintenance technologies for air-breathing engine mainly goes through three stages: post-maintenance, regular maintenance and condition-based maintenance[58]. Among them, post-maintenance and regular maintenance have become outdated technology due to high costs and high operational risks. Conditional-based maintenance allows faults to be detected in their early development stages[59], which can avoid serious faults and unnecessary maintenance[60]. At present, condition-based maintenance has become the research focus, which has been valued by various countries and major aircraft engine manufacturers[61].

Pratt & Whitney company launched the Engine Wise Platform to provide maintenance, repair and operations (MRO) services for air-breathing engines, and advanced artificial intelligence, big data and automation technologies are introduced to provide customized and personalized MRO service support[62]. Rolls-Royce company plans the operation and maintenance of the air-breathing engine by using big data and artificial intelligence technology. The developed automatic robot that can crawl in the engine as shown in Fig. 3[63], which can realize engine maintenance without disassembling the engine. Japan's Mitsubishi Hitachi Power Systems Corporation and Germany's Siemens Corporation have also conducted similar research.

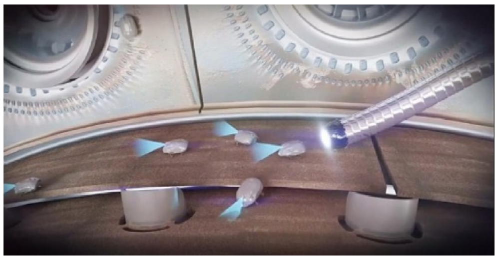

Fig. 3 SWARM insect robot used by Rolls-Royce company for intelligent maintenance[63]

The concept of intelligent diagnosis and maintenance was first put forward by developed countries, and China has made little progress in this area. The 'Remote Diagnosis and Expert Support Center of China National Offshore Oil Corporation (CNOOC) Turbine Generator' established by the 703rd Research Institute of China Shipbuilding Industry Corporation (CSIC), Harbin Engineering University, Harbin Institute of Technology and CNOOC is one of the few practical applications in engine monitoring and diagnosis in China[64].

3 Problems and challenges faced by air-breathing engine in intelligent direction

At present, the research on intelligent air-breathing engine at home and abroad is still in the initial stage, and there are some problems and challenges in all aspects. It is mainly manifested in the following aspects: unintelligent design means, long research and development (R&D) cycle, unintelligent components, insufficient wide-range regulation ability, unintelligent sensing and control means, inability to meet the requirements of wide-range performance, unintelligent detection and self-healing means, low fault detection rate, poor fault tolerance, unintelligent maintenance means, high maintenance cost and huge manpower and material resources consumption.

3.1 Problems and challenges in intelligent design

The complicated mechanism of air-breathing engine and the harsh flight environment bring huge difficulties and challenges to the innovation and application of intelligent design. As a result, the current design means are unintelligent and the research cycle is too long. The challenges are mainly in the following aspects:

(1) Under the strict restriction of size and weight, the air-breathing engine should not only bear high speed and load, but also realize various functions such as pneumatics, load bearing, lubrication and clearance control. In addition, the characteristics of the narrow stable working range and nonlinear performance response of components make engine modeling highly complicated. Therefore, how to simplify the details of engine model while maintaining the accuracy is the primary issue for developing engine modeling and simulation technology.

(2) The engine design involves multiple disciplines such as fluids, combustion, machinery, materials and control. The types of parameters, data dimensions, test methods and constraint relationships required for different disciplines are different, showing cross-coupling characteristics. For this reason, how to design a reasonable simulation system architecture, define data interfaces, and ensure orderly, efficient multidisciplinary research has become a major challenge for the intelligent design of air-breathing engines.

(3) Complex flight missions raise various performance requirements for engines, and the demands put forward by the ever-evolving war and commercial environment are varying and unpredictable. Due to complex structures and multi-disciplinary characteristics of the engine, its design cycle is too long to meet the increasing performance requirements. Therefore, how to decompose requirements for specific missions and how to conduct pre-research on modular design for typical mission requirements and shorten the development cycle, are important issues for achieving intelligent, low-cost and high-efficiency design.

In the face of the above problems, to carry out the intelligent simulation research of the propulsion system including engine digital twin model, it requires not only specific subject expertise, but also engineering experience and a macro vision of the entire engine industry. This depends on the accumulation of practice experience of the researchers, and sincere collaboration of the research team.

3.2 Challenges in the direction of intelligent components

Compared with traditional components, intelligent components adopt more advanced adjustment methods, have self-perception and adjustment capabilities, and better performance. However, due to the limitations of engine components working environment, production requirements and other aspects, the development of a new generation of intelligent components is also facing more problems and challenges, which are mainly manifested in:

At present, the technical research on intelligent components of air-breathing engine is limited by the working environment and production requirements of engine components. The challenges are mainly in the following aspects:

(1) The working conditions of engine components are varying. Many factors, such as intake conditions, flight state, control strategy and component degradation, can affect the actual working state of engine components to fluctuate in a relatively wide range. It increases the difficulty of simulation, resulting in limited technical application conditions for the developed intelligent components. Therefore, it is necessary to comprehensively analyze and accurately simulate the working state of engine components.

(2) Engine components face extreme working conditions. The engine works in a state of high-speed, high-pressure, high-temperature and high-vibration, so that the design of new intelligent components will be directly affected by the harsh environment. Therefore, there is a high demand for the practicability and reliability of intelligent component technology.

(3) Engine has strict technical requirements for its components. The intelligent component should not only have specific functions, but also meet the requirements of small size, light weight, low cost, good reliability and maintainability, long service life, environmental friendliness and modularity. For this reason, the intelligent component technology developed in the laboratory still needs to be strictly verified to be practical.

(4) Compared with traditional components, while adopting more advanced adjustment methods, intelligent components bring more complicated failure modes to the engine. Some new faults, such as the angle of the adjustable guide vane does not return, the component bearing is worn, and the action error of mechanical components exceeds the allowable error range, etc.

(5) At present, the research on intelligent component technology is not deep enough, and many technical problems need to be solved urgently. For example, the coupling relationship of influencing factors of intelligent component control, the influence on engine flow field, thrust and stability, etc., need to be further studied.

In order to meet the above limitations, the research of intelligent components has been greatly restricted, which has become an obstacle to the further development of air-breathing power plant.

3.3 Problems and challenges in the direction of intelligent perception and control

The principle and structure of air-breathing engine is quite complex, and the working environment of internal components is harsh. By enhancing the perception ability of the air-breathing engine and grasping the running state of engine in time, the running safety and reliability can be significantly improved. However, the intelligence level of traditional air-breathing engine sensing system is difficult to meet the overall intelligence requirements.

At present, the sensing system of air-breathing engine cannot adjust its own response according to the aging or the change of working environment. It does not have adaptive ability, which cannot carry out information processing and data management. It restricts the improvement and expansion of the sensor system. Meanwhile, limited by the extreme working environment, the air-breathing engine is difficult to obtain sufficient measurable information.

Moreover, the air-breathing engine intelligent perception system faces dual problems of large amount of information and little useful information. In the process of information collection by the perception system, due to the long-term operation of the engine, a large amount of data collected by the sensor has been accumulated. There is a big difference in the number of various types of recorded sample data, which easily leads to the over-fitting of the perception model and affects the perception result. In addition, the perception system is not intelligent enough, and the extraction of multi-source data features more depends on the engineer's project experience. When the experience is insufficient, the data is not well understood. Further more, if there exists a knowledge blind zone, the manually extracted features will have a greater impact on the fault diagnosis results. For online information fusion, because the measured parameters of the air-breathing engine are limited, it is easy to appear that similar perception quantities correspond to different engine states. In addition, there is also a lack of adaptive means for the degradation and sudden changes of engine characteristics.

In recent years, many scholars in China have conducted a lot of research on intelligent control methods of air-breathing engines. Great achievements have been made in engine performance optimization, adaptive control, model predictive control and life extension control by using intelligent algorithms, including artificial neural network, genetic algorithm, particle swarm optimization, fuzzy control and expert system. However, most of these results only stay in the numerical simulation stage and have not been widely used in engines. Most of the engines in service still use traditional Proportion-Integration-Differentiation (PID) control methods. Compared to the goal of achieving intelligent control, there is still a big gap. In addition, to ensure the stable operation of the engine, the current control system is designed with a large safety margin, which limits the engine performance on a wide working domain.

3.4 Problems and challenges in intelligent self-healing

To some extent, intelligent technology is human-like (biological) technology. However, different from living organisms, the engine is a complex mechanical equipment that works in extremely harsh conditions. On the one hand, with the gradual improvement of modern engine performance, the working environment of the control accessory system is getting worse, such as high temperature (fuel temperature up to 125℃), high pressure (fuel pressure up to 22MPa), strong vibration (vibration magnitude greater than 20g), large overload (load factor up to 10g) and high speed (rotation of oil pump rotating parts up to 27600r/min and oil supply up to 37700kg/h), which cause frequent failures of the engine control system. On the other hand, with the increasing control demand for intelligent engine systems, the complexity of the main components of the control accessory system has also increased significantly. The specific manifestations are the increase in the types and number of sensors, the increase in the degree of electro-hydraulic integration of the actuator, and the increase in the degree of integration of the electronic controller.

The current engine adopts traditional measurements, which cannot accurately monitor the working state and fault mode of the engine. It lacks emergency treatment technology in the fault mode, cannot meet the safety and dispatch ability requirements of the air-breathing engine. Therefore, it is not easy to realize the intelligent self-healing of the air-breathing engine system. It needs to break through two problems: (1) Real-time monitoring of engine control system health state and early diagnosis technology of sub-health state; (2) Early adaptive adjustment technology of engine control system health state and processing technology for sudden failures.

3.5 Problems and challenges in intelligent maintenance

After the 1990s, with the mature development of artificial intelligence methods, many foreign scholars have carried out research on intelligent maintenance of air-breathing engines. However, due to the complex system and poor working conditions, most of them stay in the research of maintenance and decision-making system based on health management and condition monitoring. The problem of low intelligence of maintenance means still exist, which leads to the huge cost of manpower and material resources. In China, the research on condition-based maintenance decision-making technology and system development is basically in its infancy, and there is no complete software for intelligent engine planning and dynamic scheduling.

At the same time, the engineering application of intelligent maintenance technology in air-breathing engine depends on massive historical and real-time data, while data collection and analysis depend on artificial intelligence big data method and professional data management platform. At present, with the continuous development of hardware and data management software, it is possible to generate and store big data, but the subsequent data analysis, knowledge extraction, and maintenance suggestions are still challenging research issues[65]. At present, the engine can't completely get rid of the manual analysis method, and the problem of maintenance decision-making based on big data hinders the engineering application of intelligent maintenance.

4 Development trends and prospects

Challenges are also opportunities for development. In the future, the air-breathing engine will have great development space in the six directions mentioned in this paper. With the new generation of intelligent technology, the comprehensive ability can be greatly improved. Generally speaking, the development of the next six dimensions will go hand in hand.

The improvement of the overall architecture and intelligent design level will generally lead to the development of other dimensions. Combined with intelligent components and intelligent control, the global life cycle performance of the engine can be greatly improved. Intelligence perception is the foundation of other dimensions, which provides a starting point for intelligent control, intelligent self-healing and intelligent maintenance through advanced perception means. The improvement of perception and control ability can support the development of intelligent components with self-perception and self-control. Self-healing and maintenance are complementary. With certain cross technologies, combined with the development of big data and intelligent technologies, self-healing and self-maintenance or even maintenance-free will be gradually realized, greatly improving reliability and dispatch. The development prospects and suggestions are given for the six latitudes below.

4.1 Development and prospect of intelligent design

Considering that there is no autonomously air-breathing engine in China with a full life cycle process and all aspects mentioned in the previous section is weak, the following thoughts and suggestions are put forward.

(1) In a short time, it is not advisable to rush to carry out the research on the digital propulsion system and the information physics simulation platform of related industries like the United States and Britain. Instead, China's current development level and specific situation should be fully considered. The first is to carry out rescue and sorting of historical data, improve the scale of data collection and standardization, and carry out basic tasks such as data sharing and unified management according to the position of each unit and research institute in the entire engine industry chain. The goal is to coordinate the data relationship of the entire engine industry chain, obtain the database required for high-precision numerical simulation of air-breathing engines, and find inexhaustible data sources for the establishment of a large-scale digital engine industrial Internet.

(2) Support the related disciplines of air-breathing engines to develop independent digital modeling and simulation technologies and tools for the specific problems studied, such as overall performance simulation, fluid mechanics design simulation, material mechanics simulation, etc. And strive to establish a solid technical foundation at the sub-system and module level of the engine digital twin and the industrial Internet. In addition, according to the specific characteristics of each discipline, such as parameter types, constraint relations, etc., develop interdisciplinary data variable-dimensional scaling interfaces to realize the orderly integration of discipline technology and large-scale digital design simulation systems.

(3) Integrate the whole life stage data, design and simulation systems of past and existing engines, realize multi-dimensional high-precision simulation of mature engines, establish digital twin models, and develop digital analysis, management and design improvement technologies for mature engines. At the same time, on a mature engine platform, targeted improvements and optimization studies are carried out for specific mission objectives, and digital multidisciplinary joint optimization design is realized.

(4) Aiming at several types of typical flight application tasks in the future, digitally design and simulate a number of air-breathing engines in a targeted manner. Through modular derivative design models based on general core computers and typical components, carry out

researches on overall performance matching design, component design, and variable-dimensional simulation to explore the development, use and improvement methods of mainframes. Ensure that under the guidance of meeting the overall engine design goals, unify the research of various disciplines, and jointly promote the establishment of a digital engine industry system.

4.2 Development and prospect in the direction of intelligent components

Regarding the research and development of intelligent component technology, this paper gives the following suggestions:

(1) All components and disciplines are encouraged to make full use of modern advanced material technology, electrification technology, big data technology, etc., extensively explore ideas for realizing intelligent components, and develop corresponding technologies and tools.

(2) By constructing a large-scale digital engine simulation platform, develop a high-precision and variable-dimensional digital twin model, coordinate and unify the research of various components and disciplines in the information system, provide corresponding interfaces and data scaling methods for different dimensional research, and fully realize the data sharing, multi-disciplinary and efficient interaction.

(3) At the integration level, with the goal of realizing low-cost and highly versatile building block design, the component technology research with wide adaptability, strong adjustment ability and good structural and rigidity compatibility should be carried out, so as to ensure that the intelligent component technology has the potential installation and expanding application scenarios while fully exploring, and promote the improvement of the engine performance level and the realization of high-efficiency and low-cost intelligent design.

4.3 Development and prospect in the direction of intelligent perception

On the questions about how to realize and further improve the intelligent perception of the air-breathing engine, there are several suggestions:

(1) Improve the reliability of perception. The air-breathing engine works in a high-temperature and high-vibration environment, it is necessary to conduct in-depth research on the structural strength and high temperature resistance of the sensor. At present, MEMS technology and spectroscopy technology are potential solutions to meet the harsh operating conditions of air-breathing engines.

(2) Enhance perception. For parameters that are difficult to directly measure in air-breathing engines, such as thrust, front-turbine temperature and surge margin, etc., multi-source data fusion technology and multiple measurable parameters can be used to achieve accurate estimation of unmeasured parameters. For the relevant parameters in dangerous range, protective measures can be implemented before the control system.

(3) Predict by perception. By separately adding a smart sensing and computing unit with strong computing power, the engine's component characteristics are dynamically evaluated based on the sensing data. According to the evaluation results, the engine can intelligently predict the frequency of parts replacement and overhaul.

(4) Combine intelligent perception of air-breathing engine with integrated control system. The sensing range of the engine intelligent sensing system is not limited to the perception of the engine's interior. It can relate to flight control system and fire control system to form a network. By sensing the changes of air intake conditions and surrounding environment, the control system of air-breathing engine is assisted to adjust partial parameters and formulate more reasonable control laws.

4.4 Development and prospect in the direction of intelligent control

For the development trend of air-breathing engine control system, there are three ideas for reference:

(1) Improve the modern control theory of air-breathing engines. The modern control theory should be supplemented and improved, according to the typical characteristics of air-breathing engines, such as strong nonlinearity, complex and changeable working conditions, performance degradation, external disturbance and various uncertainties. Then, it can be applied to the design of future air-breathing engine control systems. In addition, a new modeling method should be studied in combination with the great role of online adaptive model in control, which is accurate and real-time, and can provide accurate and reliable information for the control

system.

(2) Study air-breathing engine control based on intelligent algorithms. Perform real-time calculations in the control system according to the real-time sampling data based on online real-time model. The reliability of the intelligent control algorithm should be evaluated, the calculation efficiency and real-time performance of intelligent algorithm should be improved, so that the intelligent algorithm can be gradually applied to air-breathing engine control field.

(3) Carry out the research on distributed control system of air-breathing engine. Based on the 'hierarchical control' structure, the controller resources originally occupied by low-level control functions such as signal acquisition, processing and restriction protection are liberated, then the central controller has greater potential to realize advanced control algorithms such as model predictive control, active control and health management. Therefore, the overall performance of the control system can be further improved, which is of great significance to the development of intelligent control of air-breathing engine in the future.

4.5 Development and prospect of intelligent self-healing

For the problems faced by intelligent self-healing of air-breathing engines, the following innovative thinking and development suggestions are proposed:

(1) Develop the digital twin technology of engine control system based on real-time dynamic model, give full play to the super real-time simulation and health state prediction functions of the digital twin, and realize the early warning of the sub-health state of the engine.

(2) Develop model-based engine adaptive control and health management decision-making technology in order to adopt the optimal working strategy when the engine health state changes. And then realize the comprehensive optimization decision of engine safety, performance and life.

4.6 Development and prospects in intelligent maintenance

Considering the current problems and challenges of intelligent maintenance for air-breathing engines, intelligent maintenance in the future will develop towards the trend of condition-based maintenance based on health management.

(1) On the basis of the traditional maintenance task analysis, the prognostics and health management (PHM) monitoring method can be added to the lower logical analysis. Utilize advanced on-board monitoring sensors and maintenance systems to replace manual operation inspections or functional inspections to save maintenance man-hours and costs.

(2) Multi-level, multi-modal and whole-process integrated data model is the basis of establishing and realizing the integrated management of air-breathing engine life-cycle operation. Organize a large number of data involving outfield use, operation and maintenance of engines. Correlate product data at various stages, and establish a maintenance management data sharing system. It can ensure the consistency and validity of product data and provide data support for intelligent maintenance of big data.

(3) Use the Bayesian multi-source information fusion method to realize the correlation analysis and in-depth mining of engine multi-source data. Use the multi-modal deep learning architecture to realize multi-source information fusion and fault intelligent reasoning, and improve the accuracy of engine fault location.

(4) Combine machine vision technology with daily engine maintenance work to help maintenance personnel identify visual faults and measure the length or area of corresponding faults, then the errors caused by human factors can be avoided. Combine this technology with current mixed reality technology to put forward intelligent maintenance suggestions and simplify the workflow of maintenance personnel.

(5) Study the reliability model of performance degradation of the air-breathing engine based on single parameter and multi-parameter. Seek for the method of engine remaining life prediction and reliability evaluation based on system health index, and establish the prediction method of performance degradation remaining life based on multi-source information fusion.

5 Concluding remarks

Intelligent technology is a necessary means for innovative research and development of air-breathing engines in the future. In recent years, domestic and foreign researches on intelligent design, components, perception, control, self-healing, maintenance and other related fields have made great progress. However, there are still great challenges in the engineering application of related intelligent technologies. Based on the research status of intelligent technology of air-breathing engine, this paper gives some suggestions for the current challenges, and presents an outlook on the future development.

In the future, a new generation of air-breathing engines will be deeply integrated with intelligent technologies in multiple dimensions. Using intelligent components and relying on intelligent sensing and intelligent control technologies, the engines will have more complete capabilities of self-sensing, active adjustment and health management. With the in-depth application of engine intelligent technology, the performance, reliability and efficiency-cost ratio of the engine will be greatly improved, which will definitely break the bottleneck of air-breathing power technology and open up a new development situation.

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