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Performance Improvement and Material Optimization of Aviation Power Systems

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Abstract:
With the continuous improvement of aviation industry performance requirements, the increasing pressure to reduce greenhouse gas emissions and the high maintenance costs, traditional engines can no longer meet the development requirements of modern aviation in terms of high performance, high temperature resistance and low cost. Regarding the core issue of "how to improve the overall performance of engines/generators", this paper focuses on optimizing the aerodynamic/thermal design of aircraft engine turbine blades, applying advanced high-temperature materials and additive manufacturing (AM) technology to achieve lightweight and high-temperature resistance, and introducing an artificial intelligence (AI)-driven digital twin platform to perform multi-scale simulation and remaining life prediction of the entire material life cycle to support on-demand maintenance and rapid iterative design. It systematically explores ways to improve engine performance and reduce maintenance and operating costs. This article can achieve specific power improvement, weight reduction and significant reduction in maintenance costs under the premise of ensuring the reliability of aircraft engines, laying the foundation for the efficiency, lightweight and intelligence of the next generation of aviation electric-power systems.

Keywords: Aircraft generator; turbine blade; advanced materials; additive manufacturing; ai simulation; life cycle prediction.

1. Introduction

As the global aviation industry faces increasing pressure on carbon emissions, fuel efficiency, and operating costs, next-generation aircraft must operate at higher temperatures and speeds. The key to meeting these demands lies in the combination of advanced high-temperature materials (such as single-crystal nickel-based superalloys, ceramic matrix composites (CMCs), and titanium aluminum alloy (TiAl)) with additive manufacturing (AM) processes, which provide new approaches to the design and production of critical hot-end aircraft components [1].

Advanced materials and AM technologies digitally connect materials science, design, and manufacturing to achieve data-driven results. AM technologies can make components in aircraft engines lighter, thereby increasing aircraft speed. AM technologies can also shorten production cycles and minimize raw material waste [2].

This paper analyzes the structure and working principle of aircraft generators and proposes three approaches to improve the performance of aviation power systems; first, improve overall efficiency by optimizing the aerodynamics and thermodynamics of turbine and compressor blades; second, reducing the weight of the body by optimizing the use of various lightweight and heat-resistant aircraft generator housings and various materials and components; finally, use artificial intelligence to simulate the maintenance life cycle of various materials to provide data support for maintenance decisions and achieve simultaneous improvement of reliability and performance.

Furthermore, recent research trends in various countries are similar the three paths mentioned in this article. In Europe and the United States, Clean Sky 2's ENABLEH3 project and NASA-GE's ADVENT project have verified that multidisciplinary optimization of aerodynamic thermal design can increase turbine stage efficiency by up to 4%, while safely increasing the allowable turbine inlet temperature. Engine manufacturers (such as Pratt & Whitney and Rolls-Royce) have reported full-scale tests of single-crystal high-temperature alloy and ceramic-based composite blades produced using additive manufacturing technology, demonstrating their 1400°C durability and a weight reduction of more than 20%. In addition, the research center of China Aviation Industry Corporation has realized 3D printing of single-crystal blades and passed the 1,000-hour durability test. Currently, many digital twin pilots in the civil aviation fleet can predict the remaining service life of the blades. These experiments support the paper's contention that aero-thermal optimization, advanced materials, and AI-enabled digital twins are converging to deliver higher specific power, lower weight, and lower cost for next-generation aviation powertrains.

Finally, this article describes how the combination of new alloys and additive manufacturing techniques can achieve high-performance, low-cost aviation goals by reducing component weight, extending service life, and reducing total cost of ownership, as well as optimizing turbine blades.

2. Aircraft Power System

2.1 The Structure and Working Principle of Aircraft Engines

The aircraft engine as a whole is composed of six subsystems in series: the air inlet, compressor, combustion chamber, turbine, tail nozzle and accessory gearbox: the air is first rectified through the air inlet and then enters the multi-stage low-pressure and high-pressure axial flow compressor, where it is compressed stage by stage and significantly heated up; the high-pressure hot air then enters the annular combustion chamber [3], where it is mixed with the fuel sprayed from the atomizing nozzle at a precise air-fuel ratio and ignited by the igniter. The huge amount of heat energy released by the combustion causes the gas temperature to rise sharply; the hot high-pressure combustion gas then impacts the high-pressure and low-pressure turbine blades, expands and does work to drive the compressor and accessories, while at the end of the rotating shaft, part of the mechanical work is separated through the accessory gearbox to drive the fuel pump, hydraulic pump and aircraft generator; the remaining gas energy is accelerated and discharged through the mixed flow or adjustable tail nozzle, and converted into jet kinetic energy to generate thrust. To withstand extreme heat loads, the combustion chamber walls, and turbine blades are made of single-crystal nickel-based high-temperature alloys [2], ceramic thermal barrier coatings and complex built-in cooling channels. All rotating parts of the entire machine are lubricated, insulated, and monitored in real time through independent oil cooling systems, seals, and sensor networks, ultimately achieving efficient and reliable thrust output in a high temperature and high-pressure environment.

2.2 Aircraft Engine Combustion Process

In a liquid rocket engine, the combustion process begins with the precise metering and high-speed injection of the propellant: cryogenic liquid oxygen (or liquid hydrogen) and room temperature or slightly hot fuel (such as kerosene, methane, liquid hydrogen) are pressurized by a turbopump, atomized into fine droplets through hundreds to thousands of small holes in the injector head, interpenetrated in a rotating or radial jet, and instantly vaporized and mixed at the entrance of the combustion chamber; after the igniter is triggered, the mixed gas rapidly reacts chemically at a pressure of nearly 100 bar or even higher, releasing a huge amount of heat energy, causing the gas temperature to rise to 3000-3500K [4]. The high-temperature and high-pressure gas is limited by the expansion of the combustion chamber shell, and then expands through the convergent-divergent nozzle to do work, converting the heat energy into supersonic jet kinetic energy to generate thrust. During the entire combustion process, the combustion chamber walls, and nozzle neck maintain the metal temperature within the tolerable range through

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regenerative cooling (allowing the low-temperature fuel to flow through the wall first to absorb heat). At the same time, the speed of sound generated by the intense combustion is accompanied by turbulence and chemical imbalance, which requires precise control of the injection angle, pressure and mixing ratio to ensure combustion efficiency, thermal stability, and engine life [3, 5].

2.3 The Role of Parts During Combustion

During the high-pressure combustion phase of a liquid rocket engine, a number of key components work together to ensure that the propellant is fully atomized, stably ignited, and maintains structural integrity under extreme heat flow: First, the injector head (composed of collision holes, swirl cups, or pint-type nozzles, etc.) atomizes liquid oxygen and fuel into micron-sized droplets at high speed and evenly distributes them in a predetermined mixing ratio; then, the ignition system (spark plug, piezoelectric igniter, or pilot torch) initiates the flame in the main combustion zone within milliseconds, and cooperates with the flame holder and the gradually expanding combustion chamber section to maintain turbulent reflux, thereby stabilizing the reaction and suppressing flameout; the high-temperature combustion gas above 3000K produced by the combustion is covered by the combustion chamber liner and the nozzle throat plug [6]. The inner wall is equipped with a regenerative cooling channel, where the low-temperature fuel absorbs heat to protect the metal wall; the acoustic damper suppresses combustion instability; and the high-temperature combustion gas eventually expands through the Laval nozzle convergence-expansion, converting into a supersonic jet to form thrust [7]. Finally, the nozzle expansion section can be made of high temperature resistant lightweight materials such as nickel-based high temperature alloys, titanium aluminum alloys or carbon fiber reinforced carbon-based composites (C/C), and a radiation/evaporative cooling layer can be added to the outer wall [8]. The above components work closely together in an instantaneous cycle to ensure that the rocket engine releases chemical energy safely and efficiently and converts it into thrust at temperatures of thousands of Kelvins.

3. How To Improve the Performance of Aircraft Engines

3.1 Turbine Blades

The key to improving the performance of aircraft engine turbine blades through thermal optimization is to build “high temperature tolerance and efficient heat dissipation”. First, additive manufacturing (AM) is used to generate serpentine series and impingement-film composite cooling channels inside single crystal nickel-based or ceramic-based composite (CMC) blades, this can achieve secondary utilization of cooling air and reduce the extraction rate by more than 20% [9, 10]. In addition, the performance of turbine blades can be improved through aerodynamic-thermal coupling optimization. For example, CFD and multidisciplinary design optimization (MDO) are used to perform parameterized iterations on the leading-edge camber, blade chord length distribution, trailing edge thickness, and blade tip recirculation grooves to reduce shock wave intensity and secondary flow losses, thereby improving stage efficiency [11].

Finally, during the design stage, impact + film holes and serpentine internal cooling channels are arranged at the same time. With the help of 3D printing, the cooling extraction rate is reduced by about 20%, and the metal wall temperature is reduced by 50°C [9]. The above method allows the turbine inlet temperature to be increased by about100K, and the specific power to increase by about 5%.

3.2 Upgrading Materials for Key Aircraft Engine Components

In the high-temperature turbine area, the introduction of Re/Ru-containing single-crystal nickel-based superalloys and multi-layer thermal barrier coatings (TBC) can raise the upper limit of the blade metal operating temperature by about 100K [12]. In addition, in the low-pressure turbine and the rear section of the compressor, titanium aluminum (TiAl) ceramic matrix composites (CMC) are used to replace traditional nickel-based alloys, which can reduce the mass of blades and disks by 15%-30%, reduce the moment of inertia and shorten the acceleration time [2]. Finally, high-strength powder metallurgy (PM) superalloy compressor disks and high-temperature alloy bearing rings can increase the limiting speed and fatigue life, allowing higher pressure ratios and long-term high-load operation [13, 14]. The comprehensive upgrade of these materials can improve the engine specific power, reduce fuel consumption, extend the maintenance interval, and significantly enhance the efficiency, lightness, and reliability of modern aviation power systems.

3.3 AI Simulates the Life Cycle of Materials

By placing temperature, strain, vibration and other sensors on physical components to collect data in real time, and regularly supplementing nondestructive testing and accelerated test results, the full working condition information can be mapped to the digital twin with CAD+FEM/CFD multi-physics model as the core through protocols such as OPCUA/MQTT [11, 15], the twin can receive boundary conditions in real time and quickly calculate stress and temperature, call AI-physics hybrid model to predict the remaining life and output the health index, and then push on-demand maintenance or load redistribution decisions to the operation and maintenance system; each maintenance writes back the real defect data, then the online correction model is updated to form a closed loop of design, manufacturing, and operation and maintenance, thereby significantly reducing the unplanned downtime rate and compressing maintenance and iteration costs. By collecting data in real time, the "virtual body" can evolve synchronously with the physical body, and then the fast multi-physics computing and AI analysis of the twin body can be used to perform health prediction, decision optimization and continuous closed-loop correction, which can reduce the unplanned downtime rate and further compress maintenance costs and design iteration cycles.

4. Conclusion

The efficiency improvement of aircraft engines can be attributed to the three main lines of "high temperature tolerance, lightweight design, and intelligent operation and maintenance": First, implement aerodynamic-thermal coupling optimization for turbine blades, use CFD/MDO to reshape the three-dimensional profile, and use 3D printing to construct serpentine internal cooling channels, impact + film holes, and through-wall micropores, so as to reduce the cooling extraction rate, reduce the metal wall temperature, and allow the upper limit of the turbine inlet temperature to be increased.

Secondly, introduce advanced high-temperature lightweight materials such as Re/Ru single-crystal nickel-based superalloys, TiAl and CMC, and superimpose multiple layers of TBC/EBC, which can reduce the weight of blades and disks by 15-30%, increase service life, and improve engine specific power.

Finally, use the digital twin framework to map online sensor data (temperature, strain, vibration) and non-destructive testing and accelerated test results to high-fidelity CAD+FEM/CFD models in real time, and use AI-physical hybrid networks to predict the remaining life, output health index and on-demand maintenance strategies, forming a design-manufacturing-operation closed loop.

The above methods can reduce maintenance and operating costs. In addition, combined with the combustion chamber acoustic damper to suppress instability, fine end zone sealing and FADEC dynamic cooling control, the above measures have achieved a coordinated leap in engine efficiency, lightness, and intelligence, while providing a more stable and high-power density mechanical drive for aircraft generators.

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