Civil Aircraft Engine Development: Past Innovations and Future Technologies

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Abstract. Since the 1940s, civil aircraft engines have experienced five generations of technological innovation, evolving from early turbojet engines to today's advanced geared turbofan engines. This continuous evolution has significantly promoted improvements in aviation transportation efficiency, economic performance, and environmental sustainability. This article systematically reviews the technological development trajectory of several generations of gas turbine engines, highlighting key breakthroughs, technical milestones, and the application background that drove each major advancement. Successive innovations are shown to be the inevitable response to escalating environmental pressures, shifting market demands, and the rapid progress of materials science and manufacturing processes. Looking forward, variable cycle engines, hybrid-electric propulsion systems, hydrogen fuel technologies, and sustainable aviation fuel (SAF) are expected to become critical pathways for overcoming current thermal efficiency bottlenecks and achieving the long-term goal of zero-carbon aviation. Meanwhile, the civilian application of hypersonic technology, though promising for future high-speed travel, still faces substantial challenges in areas such as thermal management, system reliability, and cost control. Through a comprehensive historical analysis combined with forward-looking technological prospects, this article provides an important reference for understanding future development trends in aviation engine technology and for identifying key directions in the pursuit of sustainable aviation advancement.

Keywords: Civil aviation engine; technological evolution; turbofan engine.

1. Introduction

As one of the key technologies in the aviation field, the development of engine technology often drives the progress of the entire aviation technology. In the field of civil aviation, facing dual pressures of decarbonization and operational efficiency, the aviation industry must overcome limitations of traditional Brayton-cycle engines, such as thermal efficiency bottlenecks. Traditional engines based on the Brayton cycle have problems such as high fuel consumption, dependence on fossil fuels, and thermal efficiency bottlenecks. To address these challenges, researchers can try to find solutions in the field of innovation, such as adaptive cycle technology, which dynamically adjusts parameters such as bypass ratio and compression ratio to switch the optimal cycle mode in different flight phases, in recent years, GE Aviation's "RISE Project" has achieved dynamic adjustment of the bypass ratio at various stages of flight through the combination of open rotor and variable cycle technology, and is expected to increase fuel efficiency by 20% [1]. At the same time, research has shown that the hybrid technology of electric propulsion systems and traditional engines is an important direction for coping with carbon emission pressure [2].

Looking back at history, the development of aircraft propulsion systems can be divided into two eras, the piston era and the jet era, and will enter the hypersonic era in the future. The power unit of the piston era is the piston engine, which relies on the reciprocating motion of the piston to drive the propeller to rotate to provide power for the aircraft. After World War II, speed became one of the main pursuits of aircraft development. The birth of the jet engine in 1939 marked the arrival of the jet age. The turbojet engine can enable aircraft to break the speed of sound. Civil aircraft can achieve faster travel speeds and shorten flight time through jet engines. However, early turbojet engines had problems such as high fuel consumption. With the development of the aviation industry, people have put forward higher requirements for the economy, comfort, and environmental protection of aircraft. The turbofan engine has met these needs well due to its advantages such as high fuel efficiency, high thrust-to-weight ratio, and low noise. So far, jet engines have gone through four generations of development. Researchers are also actively developing fifth-generation aircraft engines and power plants capable of achieving hypersonic flight, hoping to meet the ever-increasing environmental protection, economic, and performance requirements in the future.

This paper aims to sort out the development of civil aircraft engines and discuss future development directions and challenges. As piston engines have withdrawn from the mainstream civil aviation market, this article will focus on sorting out the development and application of air jet engines in civil aircraft. In the following paragraphs, the article will briefly introduce the working process and principles of the two engines. After that, the subsequent paragraphs will mainly focus on the historical background, technological breakthroughs, and performance changes to compare civil aircraft engines at different stages.

2. Basic principles

Air jet engines can be divided into compressor-free and compressor-based engines. Compressor-based engines include turbojets, turbofans, turbopropellers, turboshafts, and propfans. Their working medium is gas, and they all have turbines, also known as gas turbine engines. In gas turbine engines, the Brayton cycle is the theoretical basis, which includes four ideal processes: isentropic compression, isobaric heating, isentropic expansion, and isobaric cooling. Although in actual engines, the cycle is open and the gas is not recycled, the core thermodynamic process is consistent with the Brayton cycle [3]. This section will mainly introduce the working process and principle of early typical turbojets and today's mainstream turbofan engines.

First of all, the turbojet engine can be divided into five parts: compressor, combustion chamber, turbine, afterburner, and tail nozzle. Its working process is as follows in Figure 1.

The outside air enters the engine through the intake duct and is pressurized by the compressor before entering the combustion chamber. It is mixed with the supplied fuel and burned in the combustion chamber. The high-temperature and high-pressure gas formed expands in the turbine. The high-temperature and high-pressure gas expands and impacts the turbine blades, driving the turbine to rotate at high speed. The turbine and the compressor are mechanically connected through a coaxial shaft, and part of the energy is transferred to the compressor to maintain the compression cycle. The remaining gas expands and accelerates through the tail nozzle. All the energy is used to increase the kinetic energy of the gas in the exhaust system, so that the gas is ejected backward at high speed to generate thrust [4].

Compared with turbojet engines, turbofan engines have low-pressure (fan) and high-pressure compressors. The gas flows through the inner and outer ducts in the engine. The ratio of the air flow through the outer duct to the air flow through the inner duct is called the bypass ratio. Its working process is shown in the following Figure 2.

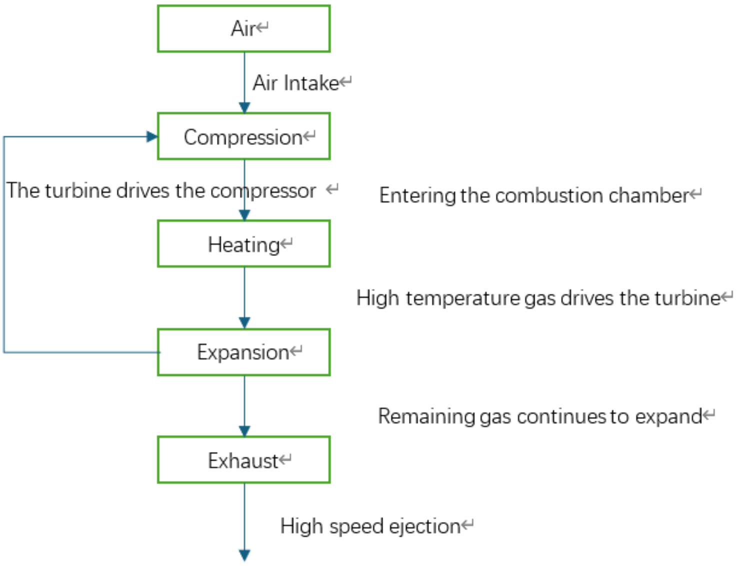

Fig. 1: Working process of the turbojet engine

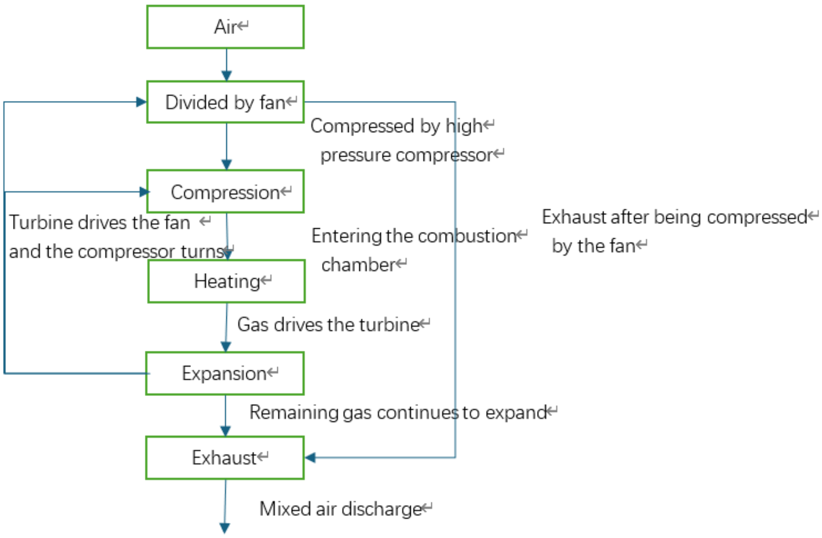

Fig. 2 Work process of turbofan engines

The air enters the fan through the intake system and is pressurized. It is divided into two airflows, the inner and outer airflows. The outer airflow enters the outer duct and bypasses the core engine. It is directly discharged after only initial compression by the fan. The inner airflow enters the inner duct and undergoes a working process like that of a turbojet engine. Finally, the outer and inner airflows are mixed and discharged, completing the cycle.

In a turbofan engine, the total thrust generated = bypass thrust + internal duct thrust. In a high bypass ratio engine, the low-temperature, high-speed airflow in the external duct is ejected directly, generating most of the thrust [5].

3. Development

3.1. First-generation turbojet engine

After World War II, the demand for high-speed flight in the aviation field surged, and piston engines could no longer meet it. Against this background, the first generation of turbojet engines was born, achieving a breakthrough in supersonic speed. The emergence of jet aircraft such as the Pratt & Whitney JT3C marked the entry of civil aviation into the jet age.

The first generation of turbojet engines is based on the Brayton cycle, a pure turbojet design with a bypass ratio of 0. Compared with piston engines, turbojet engines have fundamental differences in working principles and structural design. Turbojet engines use a continuous working cycle of compressor-combustion chamber-turbine-nozzle to generate thrust through high-speed jets. This structure is more efficient at high altitudes and high speeds, while piston engines rely on reciprocating pistons to drive propellers, and the propeller efficiency drops sharply when approaching the speed of sound. In addition, piston engines are limited by the mechanical speed of the crankshaft and propeller, while turbojet engines directly accelerate the airflow through jets without relying on the mechanical movement of the propeller.

The turbojet engine eliminated the complex mechanical transmission components and adopted a continuous gas flow and combustion process, which greatly improved the energy conversion efficiency and enabled the aircraft to break the speed of sound limit. The engine thrust range at this stage was 50- 80kN, successfully breaking the speed of sound limit. However, the fuel efficiency was about 40g/(kN·s), and the noise was loud, exceeding 120 decibels (PNdB) during take-off, which made it difficult to meet the economic and environmental protection needs of civil aviation [6].

3.2. Second Generation Low Bypass Ratio Turbofan Engine

In the 1960s and 1970s, the oil crisis broke out, fuel costs rose sharply, and airlines put forward higher requirements for the fuel economy of engines. The second-generation low-bypass-ratio turbofan engine came into being. Engines such as Pratt & Whitney JT8D and General Electric CF6 are widely used in passenger aircraft such as Boeing 727, 737, and DC-10.

The second-generation low bypass ratio turbofan engine introduced an outer duct with a bypass ratio between 1 and 5. The fan is located at the front end of the engine. Part of the air enters the outer duct directly after passing through the fan, and the other part of the air enters the inner duct. After further compression by the high- and low-pressure compressors, it enters the combustion chamber and mixes with the fuel for combustion. The outer duct air and the inner duct gas generate thrust separately or together. This design takes advantage of the low energy consumption of the outer duct air and improves the propulsion efficiency of the engine. At the same time, the use of multi-stage turbines more effectively recovers the energy of the gas and drives the fan and compressor to operate.

The thrust range of the second-generation low bypass ratio turbofan engine is increased to 80 - 200kN, and the fuel efficiency is reduced to 30g/(kN·s), which is 25% higher than that of the pure turbojet engine, and the noise is reduced to 100 - 110 decibels (PNdB). The introduction of external duct airflow balanced speed and economy for the first time, but combustion efficiency and material temperature resistance were still limited [7].

3.3. The third generation of high bypass ratio turbofan engines

With the development of the aviation transportation market, the requirements for engine reliability, fuel economy, and environmental performance have become increasingly stringent. Engines have also become more and more comprehensive. The third generation of high bypass ratio turbofan engines was born, and engines such as CFM56 and IAE V2500 have become the power options for mainstream passenger aircraft such as Airbus A320 and Boeing 737NG.

The bypass ratio of the third generation of high bypass ratio turbofan engines has been increased to 5-8, and the external bypass thrust accounts for 80%-90%. The wide chord fan blades increase air flow, improve propulsion efficiency, and have better resistance to foreign object damage. The dual rotor design allows the high-pressure rotor and the low-pressure rotor to rotate independently, optimizing the performance of the engine under different working conditions. The FADEC control system realizes precise control of the engine, adjusts the fuel supply and engine operating status in real time according to flight conditions, and improves the reliability and fuel economy of the engine.

In addition, designs such as the serrated nozzle and floating wall combustion chamber significantly reduce NOx emissions [8].

The thrust range of this generation of engines is 100-300kN, and the fuel efficiency is significantly reduced to 22g/(kN·s), which is 27% lower than the second generation. The noise meets the ICAO Chapter 3 standard and is less than 95 decibels. However, the large bypass ratio leads to an increase in the engine diameter, which limits the compatible models [7].

3.4. Fourth-generation ultra-efficient high-thrust turbofan engine

In the early 21st century, the growing demand for long-range, large-passenger aircraft in the aviation market promoted the development of the fourth-generation ultra-efficient high-thrust turbofan engine. Engines such as the General Electric GE90 and Rolls-Royce Trent 900 provide powerful power for large wide-body aircraft such as the Boeing 777 and Airbus A380.

The fourth-generation ultra-efficient high-thrust turbofan engine has a bypass ratio of 9-10 and uses a carbon fibre composite fan, which greatly reduces the weight of the fan and improves its strength and efficiency. The 3D aerodynamically optimized blade reduces airflow losses and improves the aerodynamic performance of the blade through precise aerodynamic design. The floating wall combustion chamber uses advanced cooling technology and high-temperature resistant materials to improve combustion efficiency and reduce pollutant emissions. In addition, the engine has been optimized in terms of overall structure and thermal management to further improve performance.

The thrust range of the fourth-generation ultra-efficient high-thrust turbofan engine has been greatly increased to 300-569kN, and the GE90-115B holds the thrust record. Fuel efficiency is further reduced to 18g/(kN·s), 18% lower than the third generation, and NOx emissions are reduced by 50%, meeting the CAEP/6 standard. However, composite materials have complex manufacturing processes, high manufacturing costs, and increased maintenance complexity [7].

3.5. Fifth-generation geared turbofan engine: a new power for narrow-body aircraft

In recent years, the narrow-body aircraft market has continued to grow, and airlines have put forward higher requirements for the fuel economy and environmental performance of narrow-body aircraft engines. The fifth-generation geared turbofan engine came into being. Engines such as Pratt & Whitney PW1000G and CFM LEAP provide efficient power for narrow-body aircraft such as Airbus A320neo, Boeing 737 MAX, and A220.

The bypass ratio of the fifth-generation geared turbofan engine is increased to 10-12. The fan and low-pressure turbine speeds are decoupled by the planetary gear system, so that the fan can operate at the optimal speed, improving the propulsion efficiency. The ceramic matrix composite (CMC) combustion chamber is resistant to high temperatures and is lightweight, which can increase the combustion temperature and further improve the thermal efficiency of the engine. However, the initial failure rate of the gear system is high, and its reliability requires long-term verification [9].

The fifth-generation geared turbofan engine has a thrust range of 100-450kN, and a fuel efficiency as low as 14-16g/(kN·s), which is 15%-20% lower than the fourth generation. The noise meets the FAA Stage 5 standard and is 7 decibels lower than Stage 4. However, the reliability of the gear system requires long-term verification, and the initial failure rate is high. Studies have shown that distributed control systems and fault-tolerant power management technology are the key to improving the reliability of fifth-generation engines [10,11].

4. Conclusion

Since the 1940s, civil aircraft engines have undergone five generations of technological innovation. The first generation of turbojet engines pioneered the Brayton cycle, successfully breaking the speed of sound and leading the civil aviation industry into the jet age. However, due to technical limitations, it exposed disadvantages such as high fuel consumption, high noise, and serious emission pollution, and its economic performance was poor. Then, the second generation of low bypass ratio turbofan engines introduced an external bypass to effectively divert the airflow, found a balance between speed and economy for the first time, and became the mainstream power configuration for narrow-body aircraft. With the continuous development of technology, the third generation of high-bypass-ratio turbofan engines came into being. By improving the bypass ratio and combining the wide chord fan and dual rotor design, fuel consumption and noise are further reduced to meet the increasingly stringent environmental regulations. However, due to the large bypass ratio, the engine size increases, limiting the range of compatible models. To meet the power requirements of large passenger aircraft, the fourth-generation ultra-efficient high-thrust turbofan engine uses cutting-edge technologies such as carbon fiber composite fans and has made significant breakthroughs in thrust, fuel consumption, and pollutant emissions, but it also brings problems such as high manufacturing costs and complex maintenance. The fifth-generation geared turbofan engine uses a planetary gear system to decouple the fan and low-pressure turbine speeds, and uses a ceramic-based combustion chamber, which has achieved remarkable results in reducing fuel consumption and noise, but the reliability of the gear system still needs time to verify.

These generational changes are an intuitive response to environmental and economic pressures and changes in market demand, and also benefit from the continuous progress of materials and processes. Looking to the future, civil aviation engines will show a multi-dimensional development trend. In terms of technical paths, variable cycle engines are expected to significantly improve efficiency in different flight phases by dynamically adjusting the bypass ratio, and the combination of electric propulsion systems and traditional engines can open new directions. In the field of energy, hydrogen fuel engines have become a key direction for achieving sustainable development in the aviation industry with their zero-carbon emission advantages.

Civil aviation engines have undergone five generations of technological innovation, from supersonic turbojets to efficient and environmentally friendly gear-driven turbofans. Each generation has responded to market demands and technological challenges. In the future, power system component optimization and power electronics technology innovation can serve as the key support for the integration of variable cycle, hybrid power, and hydrogen fuel technologies. However, at the same time, the reliability verification and cost control of new technologies still need to be explored continuously.

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