Full Electric Aircraft and The Electrical Motors of The Propulsion Systems

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Abstract. With the increasing awareness of environmental protection and the increasing reduction of oil resources, full electric aircraft as a green transportation tool has attracted much attention. The use of electric drive systems instead of traditional fuel power systems for full electric aircraft not only reduces reliance on fossil fuels, but also reduces emissions and noise, improving aircraft performance and safety. Electric motors are a critical component of full electric aircraft propulsion systems, providing the necessary power to drive the aircraft. This paper introduces the development history and classification of full electric aircraft and provides a comprehensive review of the various types of electric motors used in full electric aircraft propulsion, including permanent magnet synchronous motors, switched reluctance motors, axial flux motors, superconducting motors, and multi-phase motors. Additionally, the paper discusses the future trend and challenges for electric motors in full electric aircraft propulsion systems.

Keywords: Full electric aircraft, electric motors, propulsion system.

1. Introduction

With the development of economy and social progress, people have increasingly high requirements for travel safety, environmental protection, energy conservation and efficiency. The existing military and civil aircraft systems are complex and diverse, mainly including electrical systems, hydraulic systems, pneumatic systems, and fuel hydraulic systems, which reduce the operational reliability and transmission efficiency of the aircraft. In addition, global warming has become one of the biggest environmental issues, and according to statistics, the annual emissions of carbon dioxide from aircraft exacerbate the global greenhouse effect. Faced with multiple pressures such as increasing environmental pollution and global energy constraints and considering the need for aircraft to improve operational performance, full electric aircraft technology has developed rapidly in recent years. Compared with fuel powered aircraft, full electric aircraft have a single energy form, a simple drive system structure, and high reliability; full electric aircraft are easy to find the cause of faults and facilitate maintenance and detection; At the same time, the weight and center of gravity position of the fully electric aircraft will not change during flight, and the flight performance and stability of the aircraft will remain unchanged. In view of the above irreplaceable advantages, full electric aircraft has rapidly become a hot topic in the field of aerospace.

As one of the key technologies of full electric aircraft, the performance requirements of the drive motor are higher than those of conventional motors. It needs to have advantages such as high-power density, high torque overload capability, and high reliability in harsh environments and working conditions. On the premise of satisfying the output power and torque, improve the power density and torque density of the motor, reduce the overall weight of the full electric aircraft, and increase the flight distance. Therefore, under the premise of ensuring the reliability of the electric motor, how to improve the power density and torque density of the drive motor for full electric aircraft, while reducing the temperature rise of the motor under different flight conditions and improving the reliability of the operation of full electric aircraft, has become a key scientific issue to be urgently solved.

2. development history

The development history of full electric aircraft can be traced back to the early 1970s. At that time, Boeing's 737 aircraft adopted the first generation of full electric control systems. This system uses electronic controllers to control various systems of the aircraft, such as flight control, engine control, and fuel management, reducing the use of mechanical and hydraulic systems. This innovation greatly reduces the weight of the aircraft and improves its reliability and efficiency. In the next few decades, the technology of full electric aircraft continued to develop and improve：

The history of full electric aircraft dates back to the late 19th century, with the development of wind turbines. However, it was not until the 20th century that electric-powered aircraft began to emerge as a viable concept. The following is a brief overview of the history of full electric aircraft:

The pioneer of electric aircraft: In 1890, French inventor Clement Ader built a prototype electric aircraft called the Eole, which was powered by a steam engine.

Electric gliders: In 1910, German inventor Alexander Mozhaisky built an electric-powered glider that used rechargeable batteries for power.

Practical electric aircraft: By the 1930s, advances in battery and electric motor technology had made practical electric aircraft a reality. Notable examples include the Waco CG-4A electric trainer aircraft from the United States and the Bartini Stal-7 electric transport aircraft from the Soviet Union.

The use of fuel cells: Fuel cells are devices that convert chemical energy directly into electrical energy, offering a high-efficiency and clean source of power. In 2008, Airbus introduced a fuel cell-powered unmanned aerial vehicle.

Commercial electric aircraft: In 2015, German aviation company Lilium Aviation successfully test flew a vertical takeoff and landing (VTOL) aircraft powered by batteries, marking a new era for commercial electric aircraft.

Further development of full electric aircraft: Currently, research into full electric aircraft is ongoing, with scientists exploring new, more efficient and reliable batteries and electric motors, as well as the possibility of using renewable energy sources such as solar and wind power to provide power to aircraft.

Commercialization: In 2018, Slovenian aircraft manufacturer Pipistrel introduced the world's first full electric aircraft for commercial use, the Velis Electro, which received certification from the European Aviation Safety Agency (EASA). That same year, American company Wright Electric announced a partnership with EasyJet to develop a short-haul full electric passenger aircraft by 2027.

New full electric aircraft models: In 2019, Airbus launched a program called E-Fan X, which aims to incorporate electric technology into larger passenger aircraft, set to begin in 2021. Also in 2019, American company Magnix introduced the eCaravan, a nine-passenger full electric aircraft that utilizes the Magni500 electric motor.

New technological breakthroughs: With the continuous breakthroughs in technology, the performance of full electric aircraft is constantly improving. In 2020, Rolls-Royce announced a partnership with YASA to develop a high-power, high-efficiency electric motor that will provide higher performance for future full electric aircraft. In addition, several companies are working on new battery technologies such as solid-state and sodium-ion batteries to improve energy density and longevity.

3. Classification

According to different classification standards, full electric aircraft can be divided into the following types:

3.1. Classification by power system

(1) Full electro-hydraulic system: Electronically controlled hydraulic systems are used to control various systems of the aircraft, including flight control and power control systems. The advantage of a full electric hydraulic system is that it can integrate a large number of hydraulic systems inside the

fuselage, reducing the use of pipes and connectors, thereby improving the reliability and maintenance efficiency of the aircraft.

(2) full electric architecture: Electronic control systems such as electric actuators and electric pumps are used to control various systems of the aircraft. The advantage of a full electric architecture is that it can reduce the use of traditional hydraulic and fuel systems, thereby reducing the weight of the aircraft, improving fuel efficiency and range.

3.2. Classification by use

(1) Commercial full electric aircraft: Mainly used for commercial air transportation, including large passenger aircraft, medium-sized passenger aircraft, small passenger aircraft, and commercial aircraft. Commercial full electric aircraft have higher fuel efficiency and range, which can significantly reduce operating costs and carbon emissions.

(2) Military full electric aircraft: mainly used in military operations and reconnaissance, including fighter jets, helicopters, and unmanned aerial vehicles. Military full electric aircraft have higher maneuverability and stealth performance, which can improve operational efficiency and ensure operational safety.

(3) General Electric Aircraft: Mainly used in the field of personal flight and general aviation, including private aircraft, trainer aircraft, and sports aircraft. General Electric aircraft have more flexible flight performance and lower operating costs, which can meet the different needs of individuals and institutions.

3.3. Classification by flight mode

(1) Fixed wing full electric aircraft: including large passenger aircraft, medium passenger aircraft, small passenger aircraft, and business aircraft. Fixed wing full electric aircraft have higher speeds and longer flight ranges, which can meet different commercial and personal aviation needs.

(2) Rotary wing full electric aircraft: including helicopters and vertical takeoff and landing aircraft. Rotorcraft full electric aircraft have more flexible takeoff and landing performance and higher maneuverability, which can meet different requirements in the military and civil fields.

3.4. Classified by technical level

(1) The first generation of full electric aircraft: It uses electronic control systems to control various systems of the aircraft, with high reliability and efficiency.

(2) The second generation of full electric aircraft: Based on the first generation, more electronic control systems have been added, providing higher fuel efficiency and more flexible flight performance.

(3) The third generation of full electric aircraft: It adopts more advanced electronic control technology and materials, achieving a lighter, more efficient, and more environmentally friendly design, with higher performance and lower operating costs.

In general, full electric aircraft can be classified according to different classification standards, and different types of full electric aircraft have different characteristics and application ranges.

4. Research status of Drive motor

full electric aircraft is a technology that is actively researched and developed worldwide. Europe is leading the research, with Airbus launching the full electric aircraft concept E-Fan X and plans to make its first flight in 2021. The US has also made significant developments with the Boeing 787 Dreamliner, a full electric aircraft concept widely used in commercial aviation. China is also accelerating research and development with the C919 full electric aircraft, expected to make its first flight in 2021. Other countries, such as Russia and Japan, are also conducting research in this field. Many more electric aircraft/hybrid electric aircraft projects have been pursued worldwide, including the DEEL and MORE electric aircraft projects in Europe and the X-57 Maxwell electric aircraft project in the US.

In these FEA designs, the drive motor is crucial to full electric aircraft. Full electric aircraft drive systems require high motor efficiency and torque density.

4.1. Outer rotor permanent magnet synchronous motor

Direct drive permanent magnet motors are widely used due to their simple structure and lack of gearbox intermediate links. Yusuke et al. comprehensively compared outer rotor and inner rotor permanent magnet motors with different pole slot fits. The research results show that the output torque and power of outer rotor permanent magnet motors with the same size are larger than those of inner rotor motors, which is more conducive to achieving high power density [1]. Byeong Mun Song et al. designed a 20 pole 24 permanent magnet synchronous motor and applied it in full electric aircraft. The motor has high efficiency at low speeds, with a peak torque density exceeding 10 N · m/kg [2]. NASA has developed an outer rotor permanent magnet synchronous motor for light unmanned aerial vehicles, which has a mass reduction of 13.3% compared to the inner rotor motor. At the same time, the aircraft's various sports performance has not decreased [3,4]. Shan Xi from Harbin University of Technology designed an external rotor permanent magnet motor for full electric aircraft and analyzed how to achieve lightweight design while maintaining electromagnetic performance and mechanical strength [5]. Luo Xueqin of Harbin Institute of Technology has designed three design schemes for the performance indicators of drive motors for full electric aircraft: 16 pole 24 slot, 20 pole 24 slots, and 22 pole 24 slots. The calculation results show that the power density of the three electromagnetic design schemes is higher than 4.59 kW/kg, meeting the requirements for high power density of the drive motor [6]. According to the current research status of the existing literature, in situations where the speed range is not large or the cooling is good, the direct drive external rotor permanent magnet motor for full electric aircraft is the most suitable choice. Rotex Electric manufacturers have designed multiple high-performance external rotor permanent magnet motors in models REX, REB, REG, and RET. Among them, the REG30 type external rotor permanent magnet motor has been successfully applied to the full electric aircraft Cri-Cri, as shown in Fig. 1. The continuous power density of the motor is 5kW, the peak power reaches 10kW, the maximum rotational speed is 6000r/min, and the motor weight is 1.95kg. However, it is uncertain whether it is the weight of the complete machine or the weight of the effective material. The University of Nottingham team has designed a high torque density external rotor permanent magnet synchronous motor for aerospace traction, with a peak power of 60 kW and a continuous operating speed of 100 r/min, as shown in Fig. 2. In this paper, the electromagnetic design of a traction motor is conducted from the perspective of motor topology, and an analytical calculation model for accurately predicting the magnetic field of the motor is proposed. The magnetic field distribution in the air gap and the permanent magnet region at different operating points is analysed [7].

Fig. 1 Driving motor of REG30

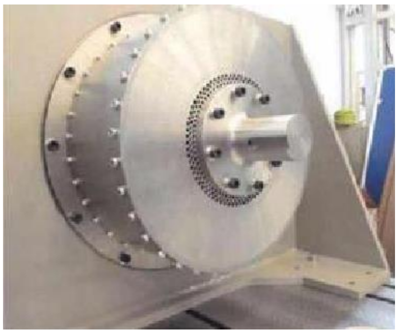

Fig. 2 Driving motor of University of Nottingham, UK

4.2. Axial flux permanent magnet synchronous motor

Due to its compact structure, high power density, and high efficiency, axial flux permanent magnet synchronous motors (AFPMSM) are widely used in automotive systems, manufacturing systems, household appliances, electric tools, aerospace, and other applications [8]. Therefore, axial flux permanent magnet motors have a promising application prospect in full electric aircraft and are suitable for driving applications in full electric aircraft. The Slovenian Pipistrel company has built a number of reliable, low weight, high power, and efficient direct-drive axial flux permanent magnet synchronous motors, namely, EMRAX188, EMRAX208, EMRAX228, EMRAX268, and EMRAX348, which are widely used in the fields of automobile, racing, off-road, marine, industrial, and aerospace. It has also manufactured the first and third full electric aircraft in Slovenia and the world. Fig. 3 shows multiple model prototypes of EMRAX.

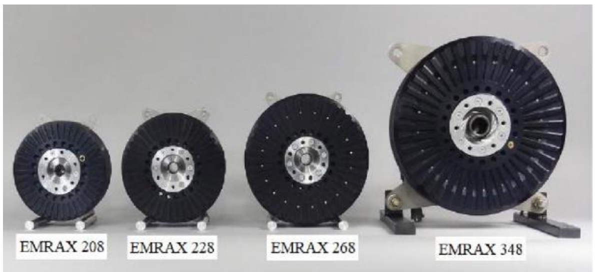

Fig. 3 AFPMSM from Slovenia of Pipistrel

4.3. Stator core slotless permanent magnet motor

In [9], an unmanned aerial vehicle drive system with four slotless permanent magnet motors was designed to improve power density and efficiency. However, the absence of stator slots also means a decrease in magnetic field strength. Therefore, it is considered to add Halbach, which can strongly strengthen the magnetic field on one side, to the rotor and combine it with a slotless stator to compensate for losses. At the same time, traditional permanent magnet synchronous motors have large cogging torque, such as magnetic field modulated permanent magnet synchronous motors and vernier type permanent magnet synchronous motors. The cogging torque can generate large torque ripple, and the main advantage of slotless motors is that the cogging torque is absolutely zero, making them very suitable for propulsion. On the other hand, the stator slotless eliminates the harmonic component of the magnetomotive force teeth, thereby ensuring a stable output torque of the permanent magnet motor.

4.4. Superconducting motor

Some scholars are committed to the research of superconducting motors. Compared with conventional copper wires, superconducting motors can achieve higher current density in extremely low temperatures, with a power density of 10-20kW/kg and a torque density of 35N · m/kg. In large motors, superconducting motors have more obvious advantages. In [10], the power level of superconducting motors reaches the megawatt level, with a power density expected to reach 20kW/kg, and the mass of superconducting motors is only 1/5 of that of traditional motors.

4.5. Switched Reluctance Motors

Switched reluctance motors can achieve high power density at high rotational speeds and have strong robustness. Ref. [11] proposes a new type of switched reluctance topology with permanent magnet assisted segmented rotor and applies it to the field of full electric aircraft. This scheme not only has the advantages of SRM, but can increase the electromagnetic output torque by 25%, ensuring a torque density and power density similar to that of permanent magnet motors.

4.6. Multiphase permanent magnet motor

The multiphase permanent magnet motor drive system has the characteristics of high output power, strong fault tolerance, and high reliability, which meets the performance requirements of full electric aircraft drive motors. Its overall electromagnetic performance is superior to traditional three-phase motors. Therefore, multiphase motors are the preferred drive motors for full electric aircraft.

In 1969, scholars proposed the concept of a multiphase motor and confirmed that the torque ripple of a five-phase motor is smaller than that of a three-phase motor, but the harmonic content of the stator winding current is large, leading to an increase in stator core loss. In the following decades, scholars have conducted a large amount of research on polyphase motors. Common polyphase motors include five-phase and six-phase motors, as well as 12-phase and 15-phase motors with multiple winding combination modes. As the number of motor phases increases, the fault-tolerant ability and torque ripple of the motor will improve, but the control circuit and control algorithm are more complex. Combining various factors, five-phase or six-phase motors are mostly used.

4.7. Comparison of different motor types

These motors are all different types of permanent magnet synchronous motors, and there are some differences and differences in their structure, working principles, characteristics, and applications.

Outer rotor permanent magnet synchronous motor: The rotor is a permanent magnet, and the stator is an electromagnetic winding. The magnetic field between the stator and rotor interacts to generate electromotive force and torque. Its rotor structure is relatively simple and suitable for high-speed, high-power, and high-efficiency applications. For axial flux permanent magnet synchronous motor, the stator and rotor are both planar structures, and the magnetic field is transmitted in the axial direction. Its compact structure and high-power density are suitable for applications requiring high torque density and small volume. For stator core slotless permanent magnet motor, the surface of the stator core has no slots, and the windings are directly wound on the core. Its simple structure and low electromagnetic losses make it suitable for low speed and high torque applications. For superconducting motor, the rotor is made of superconducting material and generates electromotive force and torque through electromagnetic induction. It has zero resistance and high current density, making it suitable for applications that require high magnetic fields and high efficiency. For switched reluctance motor, the rotor is made of soft magnetic material and generates electromotive force and torque by controlling the magnetic resistance on the stator. Its simple structure eliminates the need for permanent magnets and is suitable for high-speed and high-precision applications. For multi-phase permanent magnet motor, the stator and rotor have multiple phases, which are used to generate electromotive force and torque through electromagnetic interactions between different phases. Its structure is complex, but it has the characteristics of high efficiency, high power density, and high accuracy. It is suitable for applications that require high performance and precision.

In general, different types of permanent magnet synchronous motors have their own advantages and disadvantages, and appropriate motor types should be selected based on specific application needs. Wenping Cao et al. comprehensively compared and studied the fault tolerance, power density, efficiency, vibration and noise of induction motors, reluctance motors, and permanent magnet motors for small full electric aircraft, and concluded that permanent magnet motors are more suitable as drive motors for full electric aircraft [12]. Permanent magnet motors are currently the preferred solution. For large full electric aircraft, superconducting motors have a broader development prospect.

5. Future development and outlook

Further development of full electric aircraft: Currently, research into full electric aircraft is ongoing, with scientists exploring new, more efficient and reliable batteries and electric motors, as well as the possibility of using renewable energy sources such as solar and wind power to provide power to aircraft.

Commercialization: In 2018, Slovenian aircraft manufacturer Pipistrel introduced the world's first full electric aircraft for commercial use, the Velis Electro, which received certification from the European Aviation Safety Agency (EASA). That same year, American company Wright Electric announced a partnership with EasyJet to develop a short-haul full electric passenger aircraft by 2027.

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New technological breakthroughs: With the continuous breakthroughs in technology, the performance of full electric aircraft is constantly improving. In 2020, Rolls-Royce announced a partnership with YASA to develop a high-power, high-efficiency electric motor that will provide higher performance for future full electric aircraft. In addition, several companies are working on new battery technologies such as solid-state and sodium-ion batteries to improve energy density and longevity.

In the future, the development of full electric aircraft drive motors will mainly focus on the following aspects:

High power density: In order to improve the flight performance and range of full electric aircraft, the drive motor needs to have a high-power density. This can be achieved through the adoption of more efficient materials, design, and manufacturing processes.

High efficiency: The high efficiency of the drive motor can reduce energy loss and heat emissions, thereby improving the energy efficiency of full electric aircraft.

Integration: In the future, full electric aircraft drive motors will be more integrated, including in the fields of motors, controllers, and sensors. This will reduce system complexity, improve reliability, and reduce costs.

Intelligence: In the future, drive motors will have a higher level of intelligence, such as the use of advanced control algorithms and artificial intelligence technology, thereby improving the performance and safety of full electric aircraft.

Overall, the future full electric aircraft drive motors will be more efficient, integrated, and intelligent, providing strong support for the development of full electric aircraft.

6. Conclusion

In conclusion, the development of full electric aircraft and the propulsion systems based on electrical motors represents a significant breakthrough in the aviation industry. The advantages of electric aircraft are clear: lower emissions, reduced noise levels, and potential for improved fuel efficiency. Furthermore, the increasing demand for sustainable aviation is driving the development of electric aircraft technology, and several companies and research institutions are working to improve the technology's reliability, range, and performance.

The electrical motors of the propulsion systems used in electric aircraft are critical components, and their efficiency and power output directly affect the aircraft's performance. Advances in electrical motor technology have enabled electric aircraft to achieve greater range, speed, and payload capabilities, making them more competitive with conventional aircraft. However, there are still challenges to be addressed, such as the need for lightweight and high-performance batteries, improved thermal management, and the development of more efficient electrical motor designs.

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