New-Energy Electric Aircraft: A Review of the Developments and Challenges of Core Technologies

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Abstract. In light of the escalating global energy crisis and exacerbating environmental dilemmas, nations worldwide are amplifying their investments and research endeavors in advanced aircraft energy systems. The collective objective is the realization of aircraft that epitomize low-emission, low-noise, and minimal pollution, ensuring enhanced safety and comfort while championing energy efficiency. This paper provides a comprehensive exploration of the pivotal technology underpinning electric aircraft, offering a detailed exposition of the current developmental landscape and the inherent challenges encountered. The discussion delves into the transition from multi-electric and all-electric aircraft to entirely electric aircraft, underscoring the technological advancements and innovations propelling this shift. The paper meticulously examines the multifaceted aspects of electric aircraft technology, highlighting the significant strides made and the obstacles that persist. In addition to presenting a coherent overview of the existing state of electric aircraft technology, the paper ventures to propose potential, viable solutions to the challenges identified. This exploration contributes to the burgeoning body of knowledge, aiding the ongoing efforts to enhance the sustainability, efficiency, and efficacy of aircraft energy systems, ultimately contributing to global environmental conservation and energy sustainability.

Keywords: Autopilot; highway; automotive industry; electric vehicle; autonomous driving.

1. Introduction

Electric aircraft, which refers to aircraft powered by electrical energy, has received much attention in recent years because of the demand for more efficient, environmentally friendly, comfortable and safe aircraft [1]. On the one hand, as people's awareness of environmental protection increases, facing climate problems and energy crises, people are requiring more energy-efficient and environmentally friendly manned airplanes. Compared with piston-type general airplanes using traditional energy engines, electric airplanes using electric power systems can achieve the goals of zero-emission, low noise, high efficiency, and reduced vibration to improve comfort without causing particulate matter pollution and heavy metal pollution. On the other hand, traditional airplanes coexist with multiple energy sources, so the complex internal structure makes it inconvenient to detect and maintain, which easily has energy leakage problems, resulting in a high failure rate and poor reliability [2-5]. In contrast, the electric system can simplify the flight maintenance system through system management, thus reducing the maintenance cost and difficulty, which can improve efficiency and economy. Therefore, electric airplanes have gradually become the main development direction of research at home and abroad due to their advantages of environmental protection and energy saving.

Electric aircraft can be categorized in terms of energy source into hybrid electric and electrically powered aircraft. From this perspective, the development of electric aircraft technology can be simplified as a process from multi-electric to all-electric and from electric hybrid to electric aircraft. Electric aircraft technology improves and revolutionizes existing engine technology, researching green power energy, green materials and other technologies to improve efficiency and achieve the goals of energy saving and emission drop. The fundamental component of electric aviation technology involves electric propulsion systems distinguished by their remarkable efficiency and a superior power-to-weight ratio and long endurance, the battery technology with high energy density and long life, and the efficient overall layout design technology.

Under the pressure of aircraft fuel costs and environmental pollution, power electronics and battery technology continuously evolve, making it possible to use electric propulsion and optimize aircraft energy systems. Compared with traditional fuel engines, electric propulsion systems using high-energy-density batteries can make aircraft lighter, more efficient and more durable, which are bound to be the mainstream of the future. Although the current electric aircraft technology still has a series of development challenges, like less practical, high-cost, reliability to be verified, which has not yet reached the standard of being able to drive large aircraft, by identifying the direction of the development of power energy and electric propulsion technology, the technological breakthrough of electric aircraft is only a matter of time.

2. Classification and Working Mechanism of Electric Aircraft

The aircraft energy system consists primarily of the engine, which converts engine energy into propulsion and provides other energy to control and maneuver the aircraft. Based on the energy system, small aircraft can be categorized into multi-electric and all-electric aircraft, which refer to aircraft whose energy system is partially or fully replaced by an electric power system, respectively. Fully-electric aircrafts are categorized into solar-electric aircraft (SCEA), battery-electric aircraft (BEA), and fuel cell-electric aircraft (FCEA) based on the electric power system. The all-electric propulsion system enables unified management of aircraft systems and is lightweight, which is suitable for small, short-haul electric aircraft.

3. The Developments of Core Technologies for Electric Aircraft

Electric aircraft use batteries as energy storage devices and convert energy through engines and propellers. The core technologies for electric aircraft can be categorized into three types: high efficiency and high power-to-weight ratio electric power systems (including electric propulsion technology and integrated control technology), high energy density and long-life batteries, and efficient overall layout design.

According to related research, electric aircraft range is linearly related to electric propulsion system efficiency, battery energy density and aircraft lift-to-drag ratio, followed by aircraft lift-to-drag ratio, and finally, electric propulsion system efficiency [6]. It can be seen that the battery energy density and performance, and the aerodynamic and structural design of the aircraft all directly affect the performance of the electric airplane.

Due to the limitations of electric propulsion technology and battery technology, the main application scenarios of electric aircraft are still for low-grade simple aircraft with low energy consumption, such as powered parachutes, powered gliders, ultralight sport aircraft, light sport aircraft and drones, which are used for commercial sightseeing, aerosports competition and ground photography, etc.

3.1. Electric Power Systems: Electric Propulsion and Integrated Control Technology

Depending on the power, electric propulsion systems can be categorized into all-electric propulsion systems, hybrid electric propulsion systems, and turbo-electric electromechanical propulsion systems. In addition, there is a type of hybrid system consisting of piston power plus an electric power. A hybrid electric propulsion system is a transitional technology between a traditional fuel power system and an all-electric power system, which is recharged by burning fuel to decrease the aircraft dead weight, extend the life of the aircraft, and improve the overall performance in order to solve the current problem of insufficient energy density of the battery to achieve long range and high speed [7-9]. Similarly, the turbine-motor propulsion system charges a generator. Unlike it, the all-electric propulsion system completely realizes electric drive without fossil fuel combustion, which enhances the maneuverability and usability of the aircraft, reduces the self-weight and the maintenance cost, which can fundamentally achieve the energy-saving and environmental protection goal of zero-emission, while completely removing the dependence on fuel. The battery-driven motors drive the propellers to generate power. Its heat dissipation method is chiefly air-cooled and water-cooled. Air-cooled simple structure, small space occupation, lightweight but low efficiency; water-cooled high efficiency but complex structure, large weight, large space occupation, and energy consumption [10].

Electric propulsion systems are highly efficient, zero-emission, low cost, reliable and safe, and possess excellent flight performance and maneuverability characteristics. For electric power systems, the key technologies are centered on the motor and its controller. The power-to-weight ratio of an electric motor is affected by various aspects such as the type of motor, rated speed cooling method, etc. The maximum power-to-weight ratio of an ideal electric motor is usually less than 20 kW/kg. For improving the power-to-weight ratio of an electric motor, the key point is to reform and innovate the thermal design, magnetic performance design, cooling design and other technologies of the electric motor. In addition, for the electronics integration technology, the most critical is the robust electrical network, i.e., to maintain the stable operation of the independent electrical network of the electric airplane, to provide reliable power to the airplane and to manage the loads as needed. This is because the power electronic nonlinear loads on the aircraft generate many harmonics and noise, which cause system instability and efficiency degradation [11-13].

3.2. Energy System: High Energy Density Batteries

Currently, motors are powered by fuel cells, batteries, solar cells, supercapacitors or power beams. For storage batteries, the main current sources are lithium-ion batteries. These are mature products that can be used in electric airplanes, but there is room for further improvement in energy density. Unlike rechargeable batteries, metal-air batteries generate electricity by adding metal and replacing the electrolyte, which requires the consumption of metal processed by a special process. Graphene batteries, despite their theoretically high energy density, are currently a controversial application prospect.

Fuel cells mainly use proton exchange membrane fuel cells (PEMFC), and the current application in aircraft is mainly hydrogen fuel cells. The small density of hydrogen and liquid hydrogen requires a large volume or high-pressure container for storage, while hydrogen fuel cells have high energy density but low power density to be used in conjunction with lithium-ion batteries with high power density. The common features of lithium batteries and fuel cells are high energy storage density, high safety and reliability, long life, adaptability, durability and convenient charging.

Solar cells convert light energy into electricity through the photoelectric effect or photochemical reaction. Currently used in airplanes are mainly thin-film solar cells working with a photoelectric effect. Its main representative index is the photoelectric conversion efficiency. Large wing area laid solar panels in the light conditions are sufficient to support flight, but the stored energy density is not enough to support the night and other altitude flights. Meanwhile, solar cells are also limited by the amount of solar radiation and weather conditions, etc. thus making solar-powered airplanes poorly maintained, inefficient, heavy, and expensive and of limited utility.

Supercapacitors through the polarized electrolyte to store energy. The energy storage process does not occur chemical reaction and is reversible; thus, can be repeatedly charged and discharged hundreds of thousands of times. Fast charging speed, discharge capacity, and power density in the battery technology of electric aircraft have a broad application prospect.

Power beam or wireless power transfer through radiation technology, magnetic field resonance technology, and inductive coupling technology or laser transmission of energy is still in the preliminary research stage and cannot be applied to electric aircraft. Battery performance is mainly affected by the energy density, quality factor, specific energy and specific power, and efficiency of the battery. Relevant studies have shown that battery energy density has a greater impact on the range of electric airplanes compared to the lift-to-drag ratio [9]. Compared to fuel oil, the current battery energy density is low and has not yet reached the practical level of fuel-fired airplanes, and its safety performance and infrastructure requirements must be demonstrated before it can be applied in large numbers.

3.3. Overall Design: Aerodynamic Design and General Layout Technology

The overall design method of the electric aircraft is similar to that of the piston general-purpose power aircraft, based on the energy balance relationship equation and force analysis, and solved by repeated iterations and mathematical methods such as successive approximation. The electric airplane design has many variables and complex functional relationships, so it needs to be innovative based on conventional methods. The main point is the overall coordination and the ability to integrate the electric power system well into the aircraft design.

An easy and feasible way to do this is to retrofit the design of an existing aircraft design, using an electric power system instead of a fuel piston power system. The retrofit design method mainly includes aircraft selection, electric power system matching design and performance analysis, and calculation of numerical parameters. In the electric power system matching design, the constraints are aircraft load space and mass, etc. For the electric power system, after obtaining the constraints parameters, the electric power system is selected. Conventional design methods carry out the performance calculation and analysis. Design tools and design support systems can be used in the process, such as basic MATLAB programs to professional software, such as HALE MOD software can be used for multi-objective optimization at high altitudes and long flight times.

Electric airplanes have lower cruise speeds, small chord lengths, low flight Reynolds numbers, and difficult aerodynamic elasticity problems, so the aerodynamic design is more difficult, and the design requirements are more demanding. It is necessary to achieve very low energy consumption and very high efficiency. Electric aircraft in the layout design also need to consider the battery assembly problems, such as solar aircraft need to calculate the solar cell array installation area and consider the sunlight conditions. Also, be aware that fuel burning in oil-fired aircraft will cause the weight of the aircraft to keep decreasing, whereas this is not the case with electric aircraft. In addition, the electric aircraft motor on the installation structure of the reaction force is relatively large, and the electrical components of the vibration requirements are strict in the structural design, in addition to the structure of the lightweight, but also to consider the key equipment vibration damping. Nevertheless, electric airplanes have greater flexibility in the overall layout due to the use of electric power systems.

4. The Challenges Encountered by Core Technologies for Electric Aircraft

Current electric airplanes are limited by electric thrust technology and battery technology, and their overall performance is inferior to that of piston general-purpose airplanes. Only when the stored energy density and the power-to-weight ratio of the electric system reach fuel-based levels can they be truly applied to electric aircraft.

For electric aircraft, a series of key technical issues still need to be resolved: the overall efficiency of the electric propulsion system needs to be further improved, and key components such as electric motors adapted to electric aircraft need a rather long research and development cycle; the energy density, charging and discharging performance, and cycle life of high-energy-density batteries need to be advanced, and their adaptability has yet to be verified; the aerodynamic design of the high-lift-to-drag ratio needs to be continued to be analyzed, and low-cost composite material structures need to be further optimized to reduce the weight of the design.

The key point of the current electric power system is to improve the performance and efficiency because of its short range, unproven safety and reliability, inability to support long-distance flight and low efficiency. Specifically, the performance of each part of the electric power system can be improved separately. The most important is to improve the engine's power-to-weight ratio, followed by optimizing the motor drive controller, in addition to optimizing the propeller structure. At present, it seems that the batteries used in electric aircraft cannot support electric aircraft to realize long-distance and long-time flight, and the performance is not stable enough. This is mainly due to the insufficient energy density of the batteries, and if multiple battery packs are used to solve this problem, it will lead to excessive weight and reduced maneuverability of the aircraft, so further development of batteries with high energy density is needed [11]. Therefore, the main challenge of the current electric airplane technology should be how to improve the storage energy density of the battery. In addition, the thermal management of battery cells does not deal well with the effects of extreme environments on battery performance.

Compared to conventional airplanes, electric airplanes have many variables, complex functional relationships, and difficult aerodynamic designs. Electric aircraft, especially solar electric aircraft, with its oversized dimensions, large deflection fuselage, large-area wing, and integrated installation of the electric power system are very unfavorable to structural design, and it is difficult to find aerodynamic design, structural design and overall layout design that can effectively satisfy the basic requirements of strength, stiffness, and aerodynamic elasticity. For the overall design, the key point is to simplify the design process and improve the layout characteristics. Specifically, for structural design, the key technology is the development of structure and material technology. The research and development of new high-strength and lightweight materials can effectively solve the problems in structural design; in terms of aerodynamic design, due to the low storage energy of electric aircraft, in order to pursue a longer range of time, the aerodynamic design biased towards glider aerodynamic design, which leads to the flight characteristics of the airplane are different from those of other airplanes of the same type, not conducive to the development of the overall layout design [11]. The thinner wing shape results in a closer distance between the upper and lower airfoils, which increases the difficulty of aircraft design and leads to an increase in deadweight, so the key point is to balance the relationship between efficiency, ease of manufacture and practicality.

5. Possible Solutions and Directions for Exploration

The goal of the electric aircraft is to exceed the performance of fuel-piston general aviation aircraft while achieving the goal of energy efficiency and environmental protection. To achieve this goal, the efficiency of the electric power system needs to be improved, the energy density of the batteries needs to be increased, and the overall design of the aircraft needs to be optimized.

The structure and design of the currently used electric motors can first be optimized to improve the power-to-weight ratio of the motors. According to relevant studies, many topologies can improve the efficiency and power-to-weight ratio of propulsion motors, and further studies can be conducted to determine which the best propulsion motor topology [13] is. Alternatively, the power-to-weight ratio of the propulsion motor can be improved by choosing a superconducting motor with high efficiency, low weight, and small size. Secondly, for the motor drive controller, in order to improve its performance in controlling various indicators such as speed and direction, the use of silicon carbide high-temperature power electronics can fully realize the high-power density converter of the power system. Overall, the key direction to improve the efficiency of the electric power system is to select high-performance components, develop energy management and thermal control technologies, improve system modeling and integration, reduce the total mass of the propulsion system and improve the total system efficiency by optimizing system components. For the high-efficiency and low-noise propeller, according to the relevant research, the fixed-pitch propeller cannot maintain high efficiency throughout the flight. The speed range that can maintain the high efficiency of the propeller is very narrow, so the variable-pitch constant-speed propeller has a higher efficiency, and in the face of its extra weight, it can be solved by reducing the weight of the propeller blades, the variable-pitch controller, and other mechanisms [11]. In addition, the power density of the electric power system can also be further enhanced by further research into other new technologies, such as the technology of controlling the speed of the motor through a microcomputer using wireless sensors [13].

For energy systems, current batteries have many problems in terms of both storage energy density and specific applications, so the solution should be to develop a hybrid propulsion energy mix along with further research and development of high-energy-density batteries. Many energy storage methods have high energy densities but do not have the advantage of requiring strong piping or isolation systems for specific applications. In developing a hybrid electric propulsion energy structure, the main development direction should be the current relatively mature lithium batteries and fuel cells. For the overall design of electric aircraft, the main solution is to focus on the design concept of energy saving and emission reduction, reduce the air mass coefficient, design efficient aerodynamic shapes, optimize the structural design, and use high-performance composite materials to achieve lightweight design; determine the shape of the aircraft with a high lift-to-drag ratio from the aspects of the aircraft layout, strike a balance between the wing chord ratio and the aircraft's infiltration area, trying to increase the surface quality of the composite materials.

In terms of structural design, reducing the air mass coefficient from structural design is also an important challenge in the design of electric airplanes. According to relevant research, reducing the empty airplane mass factor can increase the battery mass factor, which means carrying more energy. By optimizing the structural form, reducing the number of standard parts, using a large number of high-performance composite materials, improving the assembly precision and using lightweight airborne equipment, all of which can reduce the empty aircraft mass coefficient and achieve structural optimization [11]. Specifically, the use of new high-strength and lightweight materials can realize new structural forms with higher efficiency, such as truss structures and honeycomb structures, and thus break through the limits in terms of scale, shape and load-carrying capacity. The main direction of development is that, in the design of aircraft structures using lightweight and high-efficiency composite materials, under the premise of ensuring the strength, stiffness and fatigue performance of the aircraft structure, the weight of the structure should be reduced as much as possible, considering the low-cost characteristics, so as to enhance the competitiveness of the aircraft in the market.

In terms of aerodynamic design, electric airplanes make up for the lack of on-board energy by improving the lift-to-drag ratio, mostly adopting aerodynamic layout designs similar to those of powered gliders, i.e., the trapezoidal wing with a super-large spreading ratio, low speed, and low Reynolds number, the low-drag symmetric thin-winged tailplane, and the slender streamlined low-drag fuselage. These designs increase the structural weight of the wing and grow the wingspan while reducing the induced drag of the airplane.

To solve this problem, Distributed Electric Propulsion (DEP), in which multiple electric propellers are arranged at the leading edge of the wing, can be selected to utilize its slipstream effect to improve the aerodynamic efficiency and reduce the wing area and structural weight. According to relevant studies, this technology can double the lift-to-drag ratio of the aircraft, reduce the wing area by half, and significantly reduce the structural weight of the port [12]. In addition, this technology multiplies the propulsion system backup, which increases safety and allows the airplane to land safely even if it experiences battery failure or partial rotor failure. In this perspective, the main future research and development direction is the integrated design of distributed electric propulsion systems and the aerodynamic characteristics of the aircraft.

In the overall design, we can also learn from the design experience of the existing aircraft: the use of lighter-weight composite materials, through the use of culvert fans to reduce noise and increase static thrust, the battery will be distributed in the middle of the wing so that the battery can get a better heat dissipation, the addition of water-cooled EFI engine for stabilizing the range speed and charging lithium batteries, the use of large and small rotor design to take into account the propulsion support and hovering cruise; the power unit of the electric power system can be selected to arrange the electric propulsion system, and the power unit of the electric power system can be selected to arrange the electric power system and the electric power system. The power unit of the power system can be arranged at the end of the rear fuselage, the top of the drogue, or distributed on the wing to fully optimize the layout by using flexibility; the energy-saving and consumption-reducing measures can be adopted, including the use of propeller braking power, updraft, vortex power generator, and so on. In order to better design the support system, the mass-size model and aerodynamic model of the electric airplane can be established, and the model can be made more accurate and finer by collecting a large amount of basic statistical data so as to ensure the design quality.

6. Conclusion

Compared with traditional airplanes, electric airplanes have their unique advantages and application prospects, which are highly efficient, energy-saving, environmentally friendly, safe and comfortable. This new clean energy aircraft technology realizes high power-to-weight ratio efficient power conversion, high energy density energy storage, and efficient overall application design, promotes aircraft intelligence and networking, reduces aircraft manufacturing and operating costs, and reduces environmental pollution, and is bound to be the mainstream development direction of green aviation in the future. Nevertheless, there are still a series of problems with the current electric aircraft, and the key technical problems of the electric power system, energy storage system, and overall design have not yet been fully resolved, resulting in the current electric aircraft performance level low, and cannot effectively meet the requirements of use. However, the electric airplane conforms to the development trend of environmental friendliness, high efficiency and energy saving, which can strongly promote the development of related technologies and has a broad application prospect.

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