A Review of Electric Propulsion for Air Vehicle Research

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Abstract. Electric propulsion technology possesses the potential of high efficiency, low noise and low emissions. Distributed electric propulsion technology can not only provide the thrust required by the aircraft, but also the flexibility of power transmission, which makes the design of the aircraft from a larger dimension. Therefore, electric propulsion aircraft is one of the main development directions of future aircraft. Based on the electric propulsion method, the aerodynamic layout of the aircraft can be changed, and the flight efficiency can be improved by improving the lift-to-drag ratio, making the aircraft safer, more efficient, and low-carbon. This article reviews the development status of aviation electric propulsion vehicles, focusing on the characteristics of distributed electric propulsion technology and aerodynamic layout changes of electric aircraft.

Keywords: Electric propulsion technology · Distributed electric propulsion technology · Air vehicle

1 Introduction

With the development of society and the advancement of science and technology, the development of *green aviation* has become the consensus of today's society. The specific implementation methods include the development of advanced aircraft design technology, power system technology using clean energy, material manufacturing technology and flight landing technology. Noise technology, etc. [1]. In recent years, the goal of low carbon has become increasingly clear. Adopting carbon offset schemes, switching to efficient aircraft, and using renewable energy are all ways to reduce carbon dioxide emissions. A series of research projects have been carried out internationally, such as Carbon Offset and Reduction Scheme of International Aviation (CORSIA) [2], clean skies programme of the European Union, environmentally responsible aviation of NASA (ERA) and *2016 Green Aviation White Paper* and so forth.

Electric propulsion power plant is one of the feasible ways to realize low-carbon green aviation. Compared with the traditional fuel power system, the electric propulsion system has potential advantages such as high efficiency, environmental protection, low noise, low vibration, and easy maintenance [3]. It is one of the research hotspots in the field of aviation technology in the world. E-Fan aircraft of Airbus uses lightweight,

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high-efficiency generator and electric motor technologies, including the Cri-Cri, which has four electric motors to drive the propellers successfully tested flight in September 2010 and the E-Fan has four electric motors to drive propellers, which successfully test flight at the end of 2013 [4]. At the same time, Germany's Siemens, Germany's Siemens and Airbus jointly developed the E-Airbus 100-seats regional airliner concept based on a distributed hybrid electric propulsion system. Airbus and Rolls-Royce jointly developed the hybrid concept aircraft E-Thrust, which makes Track 2050 is a big step forward. Electric propulsion vehicles are also being considered as a possible way to achieve the ambitious goals of the European Union's *Flightpath 2050* [5].

Electric power for electric propulsion can be provided by the aircraft's on-board batteries or by a hybrid system using an engine. When the propulsion system is driven by an electric motor, aircraft designs that are difficult to achieve with conventional gas turbine power can be used, resulting in increased efficiency and reduced emissions. For example, Single-aisle Turboelectric Aircraft with Aft Boundary Layer (STARC-ABL) developed by NASA in the Fig. 1. Engines under the wings provide most of the thrust during takeoff, some during cruise, and the remainder is provided by electric propulsion in the tail. The aircraft tail duct of STARC-ABL is also known as Boundry Layer Ingesting (BLI), It can not only generate forward thrust when the fan rotates at high speed, but also extract and accelerate the boundary layer flowing through the fuselage and engine and then discharge it backward, improving the tail flow field, reducing the wake resistance, and increasing the fuel efficiency by 10%., significantly reducing environmental pollution [6, 7]. A similar tail propulsion system would be difficult to implement if powered by a gas turbine.

Fig. 1. The single-aisle turboelectric aircraft with aft boundary layer of NASA

The blended-wing-body N3-X aircraft concept, which studied by NASA, adopts gas turbine electric distributed propulsion system (TeDP) and full composite material, laminar flow, and wing body fusion technology, and its fuel consumption rate is reduced by more than 70% compared with Boeing 777-200LR aircraft [7].

Zunum believes that 40% of current aviation pollution comes from short-haul flights. In response to the demand for short-haul flights, Boeing and Zunum Aero have developed small hybrid electric passenger aircraft to significantly reduce flight expenses and reduce aviation carbon emissions. Compared with conventional propulsion aircraft, hybrid electric aircraft is expected to reduce carbon emissions by up to 80%, and by reducing fuel consumption, it can reduce operating costs by 40–80%. If the pure electric design is adopted, it is expected to achieve 75% noise reduction and zero carbon emissions [8] (Fig. 2).

Fig. 2. The concept picture of Zunum Aero

Compared with the mechanical transmission method, the convenience of transmitting energy through electricity is much higher, so a more flexible power arrangement can be adopted on the aircraft, and the distributed electric propulsion (DEP) system aircraft came into being. Distributed electric propulsion systems are powered by several motor-driven fans, propellers, and other devices on the wings or fuselage [9, 10] The distributed electric propulsion system can control the flow field of the aircraft more finely, so as to achieve higher efficiency, which is a very promising solution to improve the efficiency and performance of the aircraft. Compared with traditional powered aircraft, the electric propulsion system is compact, reliable and safe, and it is also conducive to the beneficial coupling between the two traditionally independent disciplines of the airframe and the propulsion system [11]. As an emerging technology, distributed electric propulsion technology involves a series of issues such as power system and propulsion layout [12]. This paper reviews the composition of electric propulsion system and the research status of distributed electric propulsion aircraft, focusing on the research progress of aerodynamic layout of distributed electric propulsion aircraft, in order to provide reference for the development of distributed electric propulsion technology.

2 The Common Distributed Propulsion System

Generally, the aircraft with distributed propulsion has more than four or even as many as dozens of propulsion units, which can better integrate the propulsion system into the airframe, to raise aerodynamic efficiency, improve flight performance and fuel consumption rate. The engines of distributed propulsion aircraft are propellers or ducted fans. Biser et al. [5] found that the DEP-6 and DEP-12 project aircraft both have a potential of reducing the specific block fuel consumption by approx. 4.2% and 5.8% respectively in case of direct driven propellers, while for a geared-drive scenario a total reduction of up to 7.6% in case of DEP-6 and 8.5% in case of DEP-12 is possible, all compared to the direct-driven baseline (BSL) aircraft SE-CS23 turboprop commuter aircraft (as shown in Fig. 3) adopted a distributed electric propulsion design concept. In a simplest way the typical twin-engine configuration could be modified by having in total four or six propellers facilitated by electrical power transfer. And as the number of propellers increases, the new aerodynamic layout has potential advantages [13]. And a reasonably spanwise-invariant loading can be produced by the installation of the overwing ducted fan DEP system [14]. The interaction of the propeller slipstream with wing aerodynamics for improvement of high-lift capabilities or the reduction of induced drag by the installation of wingtip propellers, alleviate the wing root bending moment caused by high aerodynamic forces acting on the wing and decrease the structural weight of the wing. This kind of flight control system has the potential to reduce the size of the vertical tail plane, thus, reducing its structural mass and drag contribution. The studied shows a turbo-electric aircraft configuration can only perform better than a comparable turobprop if performance and efficiency of the electrical components are improved [15]. Erhard et al. [16] evaluated the aero-propulsive efficiency of a general aviation aircraft under various propeller distributions and found propeller-wing interactions can bring about beneficial aerodynamic effects. The power unit can be located at the leading edge, trailing edge and other places in a distributed propulsion system, which will have different effects.

Fig. 3. The turboprop aircraft of CS23

2.1 The Distributed Electric Propulsion is Located on the Leading Edge of the Wing

Multiple distributed propellers are installed on the leading edge of the wing is a common distributed electric propulsion aircraft structure [17], which is characterized by a plurality of propellers distributed along the span of the wing, and these propellers are located at the leading edge of the wing. The rear wing of the propeller is in the slipstream region, and the high-speed airflow can increase the lift of the wing. The distributed propeller system increases the wing area affected by the slipstream to improve the effect of slipstream lift. There are multiple trim schemes for distributed power units, which is easily installed [16].

This concept consists in distributing propulsive power and thrust through several relatively small propellers that are installed ahead of the leading edge of the wing with the purpose of blowing their slipstream on it during takeoff and landing, increasing the generated lift.

Stoll et al. [27] tested on a four-seat general aviation aircraft to study the effect of different wing and propeller layout. It shows the aircrafts with distributed power layout are more efficient than complex traditional designs, and the lower propeller tip speed can also reduce noise. Murilo et al. [18] studies the performance of distributed electric propulsion on general aviation aircraft. It shows that when the aircraft is flying at low speed, the effect of slipstream enhancement is improved by installing multiple small propellers on the leading edge of the wing, which can reduce the wing area by 62% and increase the wing load by 131%. As shown in Fig. 4, the EcoPulse distributed hybrid electric propulsion demonstrator has three electric propellers installed on both sides of the wings to replace the original standard engine and propeller power unit. The slipstream generated by the distributed propeller has a larger area of action on the surface of the wing to increase the lift coefficient [19]. Meanwhile, the four propellers which near the fuselage are adopt a folding design, and can be folded according to the requirements of flight conditions to reduce the cruise resistance.

Fig. 4. EcoPulse demonstrator

NASA X-57 demonstrator (as shown in Fig. 5) is a typical configuration of a distributed electric propulsion system with engines located on the leading edge of the wing, which adopts a large aspect ratio wing layout to reduce flight resistance and improve efficiency. There are 12 small high-lift motors with propellers are distributed along the leading edge of the wing, which can provide lift during take-off and landing and the propeller blades are retracted into the nacelle to reduce resistance during cruising. The propellers on the wingtips on both sides can reduce the adverse effect of the wingtip vortex on the aerodynamic performance. X-57 aircraft not only takes advantage of the advantages of high battery energy utilization, low or even zero emissions, and low motor noise, but also uses generated by the addition of motor propellers through the slipstream effect during takeoff and landing to significantly improve the maximum lift coefficient of the wing. Under the same take-off and landing performance conditions, the length of the wing chord can be greatly shortened, the wing area can be reduced to 40% of the original, and the weight of the body structure can be reduced [20]. Distributed electric propulsion systems increase the degree of freedom associated with flight controls as well. NASA Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR) [21, 22] converted the internal combustion engine-powered propulsion of an existing light aircraft into a structure with 12 small electric propellers and two large propellers at the tip. The 12 small high-lift electric-driven propellers are distributed along the leading edge of the left and right wings to increase the dynamic pressure on the wing surface and improve the wing performance when the aircraft is flying at low speed. The 2 electric-driven cruise motors and propellers are located on the wingtips to provide main propulsion power and reduce the adverse effects of wingtip vortices to improvie the take-off and cruising performance of the aircraft. NASA builds a SCEPTOR 4.0 aircraft by creating SCEPTOR demonstration geometry and determining the modeling design parameters for different layout forms [21]. Flight tests have shown a significant increase in efficiency over the prototype at a cruise point of 150 knots and an altitude of 8,000 feet. The performance of distributed electric propulsion aircraft with different structures will be different. Compared with the aircraft powered by 2 propellers, the take-off distance of the aircraft powered by 16 propellers is shortened by at least 50%; the aircraft with 8 propellers has the best noise reduction effect, and the take-off distance is 43% shorter than that of the aircraft with 2 propellers [23].

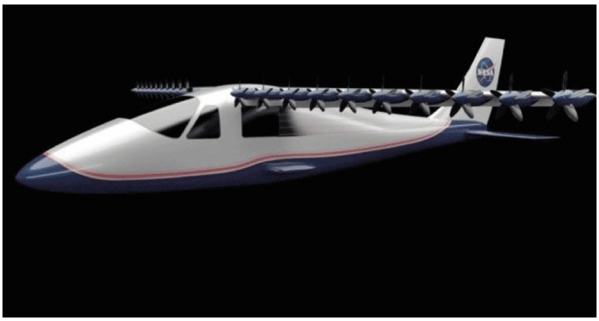

Fig. 5. NASA X-57 Maxwell aircraft demonstrator

2.2 The Distributed Electric Propulsion is Located on the Trailing Edge of the Wing

The distributed power enables a high degree of coupling between the propulsion system and the fuselage when the propulsion system is along the fuselage or trailing edge of the wing. It adopts a ducted engine configuration, and the distributed power is usually located at the tail of the wing or fuselage. The boundary layer at the fuselage or tail of the wing are suck into ducted engines to increase the lift-to-drag ratio of the wing. Hill et al. [24] studied the propulsion system of an advanced civil aircraft and found that the boundary layer inhalation effect can reduce the energy input by 9%, and the distributed arrangement of the power system can also delay the stall of the aircraft. However, the positions between the spanwise engines will still be separated when the angle of attack reaches the stall point, and the three-dimensional flow may affect the consistency of engine operating conditions [25].

SAX40 (as shown in Fig. 6) and N3-X (as shown in Fig. 7) are the typical representatives which the propulsion system of the aircraft is located on the fuselage or the trailing edge of the wing. The SAX40 is powered by nine fans. The N3-X aircraft concept utilizes a turbine electric distributed propulsion system (TeDP), with two wingtip-mounted turbine generators driving 14 electric fans. The devices that generate thrust and power are separated by TeDP. Two turboshaft engines mounted on the wingtip drive superconducting generators to generate electricity and 15 superconducting electric thrusters embedded in the fuselage to generate thrust. This new layout can achieve the goal of reducing the fuel consumption rate of Boeing 777-200LR aircraft by more than 70% [26].

Fig. 6. SAX-40

In a word, when the engine is located on the leading edge of the wing, the distributed propulsion power system of the propeller is usually used, which can effectively obtain a better effect of increasing slip flow, control the tip vortex system, and facilitate structural design and engineering implementation. When the engine is located on the trailing edge of the wing or the rear of the fuselage, the structure of the ducted fan is often used, which can effectively offset the resistance of the fuselage mainly by controlling the boundary layer.

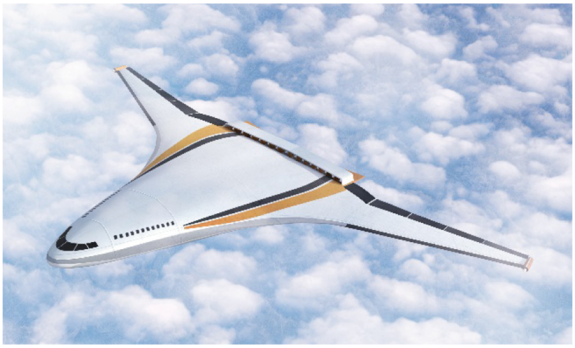

Fig. 7. N3-X

3 Application and Effect of Electric Propulsion Aerodynamic Configuration

Modern conventional civil airliners typically have an approximately cylindrical fuselage, swept-down monoplane, single vertical tail, wing crane or tail crane engine shape (as shown in Fig. 8). From piston propellers to turbojet aircraft engines, the design of aircraft aerodynamic configuration and aerodynamic efficiency are directly influenced by different types of engines. Modern large-scale civil airliners reduce drag by installing winglets, attaching deflectors to the wing and engine nacelle, and adopting a fusion of engine wing suspension configuration and blended wing body [27, 28]. The application of electric propulsion increases a new dimension to aircraft operation and aerodynamic configuration.

Fig. 8. The appearance of modern conventional civil airliners

3.1 Normal Aerodynamic Configuration

In the traditional aerodynamic configuration, in order to minimize the influence of airflow near the engine on the overall aerodynamics of the aircraft, the propulsion system is usually installed in front of the wing or near the fuselage. Airbus and engine manufacturer

Rolls-Royce's E-Fan X (as shown in Fig. 9) program, based on the BAe 146 aircraft, attempts to reduce carbon emissions with a hybrid electric propulsion system. One or two of the four engines of conventional aircraft are changed to electrically driven bypass fans, which can better meet the aircraft power requirements of the aircraft during take-off, landing and cruise phases, by taking advantage of the convenient and coordination feature of the motor to reduce fuel consumption.

Fig. 9. The concept aircraft of Airbus' E-Fan X

The hybrid aircraft concept E-Thrust (as shown in Fig. 10) was proposed based on the ducted fan installed at the tail of the aircraft to improve the performance of the aircraft by increasing energy to the boundary layer. A total of 6 electric ducted fans are installed above the wing roots on both sides to provide power for the aircraft. This electric distributed propulsion system can achieve low fuel consumption, low emissions and low noise, the overall bypass ratio of the engine can reach 20, when the aircraft needs to slow down, it can even generate electricity by the wind [13].

Fig. 10. The concept of E-Thrust

3.2 Blended Wing Body Configuration

The Blended Wing Body (BWB) blends the fuselage and wing structure into a flying wing shape. The original intention of the BWB concept is designed to maximize the overall efficiency of the aircraft by integrating the engine, wing and airframe into a single lift surface. The BWB configuration aircraft has the potential advantages of low aerodynamic resistance, high flight efficiency, light structure weight, large loading space, energy saving, environmental protection and noise reduction. It is one of the revolutionary technologies of civil aircraft that are expected to achieve the *economy, environmental protection, comfort and safety* requirements of green aviation in the future, and it is also a field that the international aviation community has been studying for many years. NASA studies have shown that the BWB can save fuel by 10%, and the noise of the BWB aircraft is 37 decibels lower than the *round* + *wing* aircraft [29].

The blended wing-body configuration created new possibilities for propulsion system innovation and integration. As shown in Fig. 11, the MAVERIC (an aircraft model used to verify and test robust innovation control) *BWB* demonstrator displayed by Airbus at the Singapore Airshow. The configuration design with a smooth transition from the wing to the fuselage shape is extremely revolutionary. This enables the entire fuselage to generate lift and reduce drag. Meanwhile, the engines are located above the fuselage, reducing noise. Compared with current single-aisle aircraft, the aircraft is expected to reduce fuel consumption by more than 20%, and its multifunctional cabin provides a new onboard passenger experience. Another example is the Airbus ZEROOe 3 zero-emission commercial airliner concept (as shown in Fig. 12), which adopts a *blended wing body* configuration and is equipped with a distributed turbofan engine power system. Its ultra-wide fuselage provides multiple options for storing and distributing hydrogen fuel.

Fig. 11. The model of MAVERIC

3.3 The Truss-Braced Wing (TBW) Configuration

The appearance of the Truss-Braced Wing (TBW) configuration is similar to the traditional *tubular fuselage* + *wing* configuration, but a truss structure is used to support the

Fig. 12. The blended wing body passenger aircraft concept scheme of ZEROe

wings, as shown in Fig. 13. Compared with the traditional cantilever beam wing, TBW bears part of the load on the truss, which can reduce the bending moment of the wing root, and can increase the wing aspect ratio with the same weight. The larger the aspect ratio, the larger the lift-to-drag ratio and the smaller the induced drag, the TBW configuration can reduce fuel consumption by 10% or even higher than the traditional cantilever wing configuration. In addition, the TBW configuration can reduce the thickness of the airfoil, which will significantly reduce the wave resistance during transonic flight, and the thin airfoil is more conducive to the realization of natural laminar flow [5].

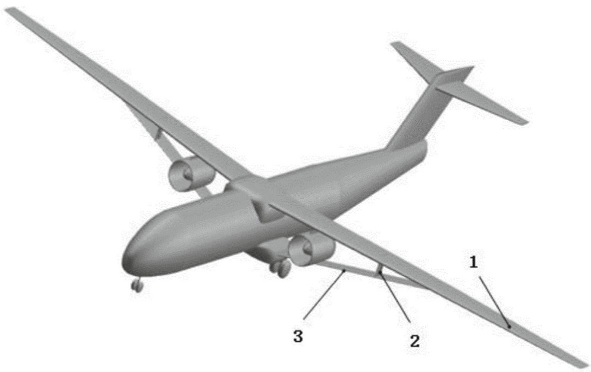

Fig. 13. The configuration of Truss-Braced Wing

The Boeing and NASA studied the Subsonic Ultra-Green Aircraft (SUGAR) (in Fig. 13) [30], which own Truss-Braced Wing (TBW), T-tail layout, and high aspect ratio. One end of the wing is supported by a strut. Compared with the traditional wing, the TBW can reduce the thickness and sweep angle of the wing, increase the wingspan, and improve the lift. The support beam can effectively reduce the bending deformation of the wing, relieve the load on the root of the wing, and significantly reduce the weight of the wing structure. Meanwhile, the wing can be folded and tucked when the aircraft land to fit into the airport space and reduce the footprint [31]. SUGAR Volt adopts parallel gasoline-electric hybrid technology, which is mainly powered by electricity for short-haul flights, while jet fuel will replace electricity for long-term flights. The fuel engine and battery will jointly provide power during take-off. The extra thrust added by the battery can shorten the take-off time and achieve the purpose of energy conservation and environmental protection. When the aircraft reaches cruising altitude, it can be completely switched to the battery power supply mode to reduce fuel consumption and nitrogen oxide emissions [32]. Compared with traditional aircraft, the efficiency of SUGAR Volt is improved by 55%, releasing 60% less CO_2 emissions and 80% less NOx emissions during flight [33] (Fig. 14).

Fig. 14. Subsonic Ultra-Green Aircraft (SUGAR) volt

4 Conclusions

Electric propulsion technology is a potential way to improve high-efficiency energy utilization, low life-cycle carbon emissions and high noise of aircraft. It make the travel through air transportation more environmental an more efficient. This paper reviews the distributed propulsion and conventional aerodynamic layout of electric propulsion aircraft. The main conclusions are as follows:

1. The aircraft aerodynamic efficiency can be improved via the synergistic integration of thrusters and aerodynamic control surfaces. It is expected to save fuel or energy, reduce emissions, lower noise, and improve take-off performance.
2. The distributed propulsion system aircrafts are more flexible than traditional aircraft. Enabling a high degree of aircraft and engine coupling design. The distributed propulsion layout involves the research on the integration of aircraft overall, power, electromechanical and other technologies, and is likely to bring revolutionary changes to the aviation industry. Many researchers who are from different countries are actively exploring related technologies and applications, but there are still many technical bottlenecks that need to be solved urgently. After the continuous exploration of scientists, people can take an electric propulsion system aircraft which is *low-emission*

or even *zero-emission* to fly around the world, and take an *air-taxis* to achieve commuting and short-distance travel. It can contribute to the harmony between man and nature.

3. Due to the limitation of battery technology, it is difficult to meet the requirements of long-distance aviation operations for the all-electric propulsion aircraft. However, the hybrid electric propulsion is a compromise solution that comprehensively considers environmental protection, range, flight time, and economy. If the lithium battery technology can be increased by two to three times on the existing basis in the future, the all-electric aircraft can realize air transportation with higher payload and range.

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