Development and Challenge of More/All Electric Aircraft

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Abstract. With the rapid development of the aviation industry and the increasing environmental concern, the electrification of aircraft has become a leading research topic in aviation. More Electric Aircraft (MEA) and All Electric Aircraft (AEA) are two classifications of this field. MEA is designed to apply electrical structures to update traditional hydraulic and mechanical equipment, so as to improve the fuel efficiency of the aircraft, while the main propulsion power is still provided by aviation fuel. This excogitation has been developed in stages and put into commercial use. AEA is a more idealized design which aims to eliminate all forms of energy other than electrical energy on the aircraft in order to achieve higher efficiency and environmental goals. Research on AEA encounters multiple technical barriers, mainly the battery energy density. This paper introduces developments on the structures involved in the electrification of aircraft and their characteristics, then systematically analyses the main technical factors that limit the development of AEA and the possible technological breakthroughs in the future.

Keywords: Aircraft electrification, MEA/AEA, Electromagnetic interference, Energy density.

1. Introduction

With the development of economic globalization and civil aviation, the huge amount of greenhouse gases produced by more aircrafts has become an increasingly serious environmental concern. The large consumption of aviation fuel makes the proportion of aviation carbon dioxide emissions in the total amount in 2020 reach five times that of the middle of the last century [1].

To achieve the goal of sustainable development and reduce the emission of carbon and nitrogen oxides while increasing the energy utilization rate to reduce the greenhouse effect, the electrification of transportation has become a development direction worthy of research. Aircraft electrification is a reliable alternative to solve the current air transport demand and cope with the expected economic and environmental impact. There are two categories in this field, multi electric aircraft (MEA) and all electric aircraft (AEA). Although electric vehicles and ships have achieved phased success and put into use, and unmanned aerial vehicles have also proved the possibility of electrification of micro aircrafts, pure electric large aircraft is still in the stage of theoretical research and preliminary test.

There are two major technical challenges that must be solved in the design of all electric aircraft (AEA). One is that the propulsion mode of the aircraft needs to be redesigned. If the traditional propulsion method is continually applied, the weight and size of electrical components required to provide the same thrust will exceed the specification. Another problem comes from the electrochemical energy unit that provides power. At present, the energy density of all kinds of batteries, capacitors or fuel cells is far less than that of aviation fuel， while the power required for the takeoff of large aircraft can reach 30 MW [2]. Therefore, it can be considered unrealistic to provide the aircraft’s takeoff power by electric energy at this stage.

In line with this technical background, the development of more electric aircraft is much more promising in a short period. Different from directly replacing the fuel propulsion system, the design idea of MEA is applying electric drive to update other control systems of the aircraft, such as hydraulic system, pneumatic system and part of mechanical transmission system, so as to reduce the weight and fuel consumption of the aircraft [3]. Considerable progress has been made in this field, and it is expected to be put into practice in the near future.

This paper reviews the structures and technologies related to MEA / AEA, which contains actuation system, brake system, environmental control system and redesigned EPS. Then a systematical analysis will be delivered for the advantages and limitations of MEA propulsion mode compared with traditional propulsion mode, as well as the possible development direction of AEA in the future.

2. Structures of MEA/AEA

2.1. Actuation System

Flight control surface actuators are vital in the design of previous aircraft actuation systems. This traditional hydraulic control system consisted of hydraulic pumps, hydraulic pipes, hydraulic valves and other structures. The fluid pressure generated by the hydraulic pumps drives the control surfaces of the aircraft shown in Figure1, while the servo valves control the action of the actuator. The pilot's maneuver is transmitted through the mechanical circuit to the corresponding servo valves in the hydraulic circuit, and the hydraulic pump drives the actuator to operate the aircraft's control surfaces [4]. Boeing's large transport aircraft still adhere to this hydraulic actuation mode.

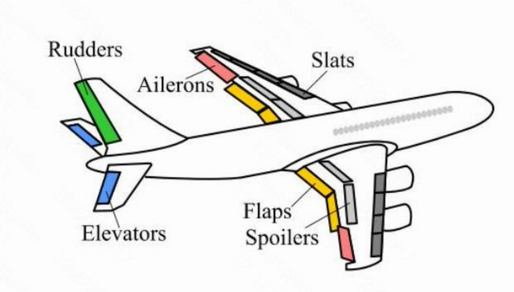

Figure 1. The aircraft control surfaces [5]

Electric actuation system for MEA has been upgraded into a combined application consists of Electromechanical Actuator (EMA) and Electro-Hydraulic Actuator (EHA). The function of EMA is to convert electrical energy into mechanical energy via the motor, and then use the developed energy to drive the control surface through mechanical operating components such as gears and ball bearings. Also, the sensors inside EMA will send the position and velocity data to the Electronic Control Unit (ECU) to accomplish the feedback current control. Figure 2 demonstrate the EMA functioning cycle.

Despite the high efficiency this direct energy conversion has, according to [6], EMA can still be seriously affected by atmospheric pressure and extreme weather environment, while embrittlement caused by thermal and structural fatigue can also make it fail. To enhance the stability, EHA is applied, an actuator which carries out a two-stage energy transmission. The transitional hydraulic energy enhances the stability of the system, but due to the use of cylinders and air pumps, the overall transmission efficiency decreases. Recent research in [2] also introduces a new type of actuator, electro-hydrostatic actuator (EHSA). The measured efficiency is almost twice than previous EHA with a similar structure.

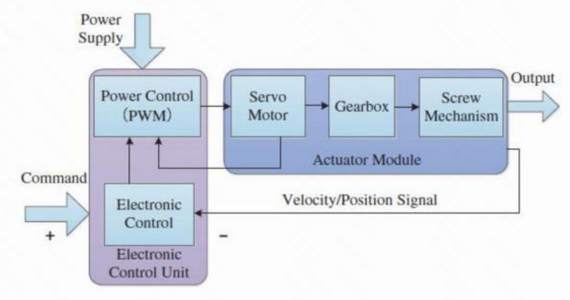

Figure 2. The function diagram for EMA [7]

2.2. Taxiing/Brake system

The taxiing/brake system of the aircraft in the take-off and landing phases is also extremely important. Many accidents occur in these two phases of flight, and the leakage of the traditional hydraulic system is a main reason. In MEA, the electric tractor replaces the traditional hydraulic system, thus reducing the noise of the landing gear, decreasing the wear level and consuming less energy. Applying electric brakes can build an instant monitoring cycle to avoid secondary harm due to the unconsciousness of abnormal. The multiple acceleration/deceleration in taxiing stages shown in Figure 3 requires high power which can reach 30MW, so the electric structures nearby the brakes must overcome the thermal and strength issues [5].

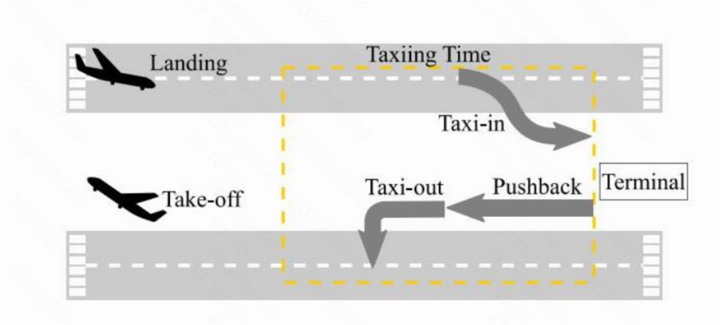

Figure 3. A typical Take-off stage for a flight [8]

Another design aims to make the aircraft accelerate on an electric platform before takeoff. The platform will provide the acceleration of takeoff by connecting with the magnetic levitation components, thus greatly reducing the fuel consumption during takeoff [9]. The general idea is shown in Figure 4. However, this technology is still in the preliminary design stage, and the solution for landing stage seems not easy to design. If this technology is put into use, the existing airport environment and equipment need to be completely redesigned.

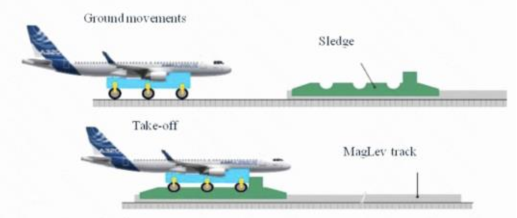

Figure 4. The separated Take-off design in [9]

2.3. Propulsion system

MEA and AEA have different objectives in the study of electrified propulsion systems. The main purpose of MEA is to replace the traditional mechanical driving structure with electronic components and improving the effective threshold of the fuel supply system, thereby increasing the energy utilization and reducing the overall weight of the aircraft [7]. Complex systems such as engine gearboxes can be replaced during electrification. However, the power source of the aircraft is still aviation fuel. Recent related studies focus on the propulsion system based on turbofan engine which shows in Figure 5.

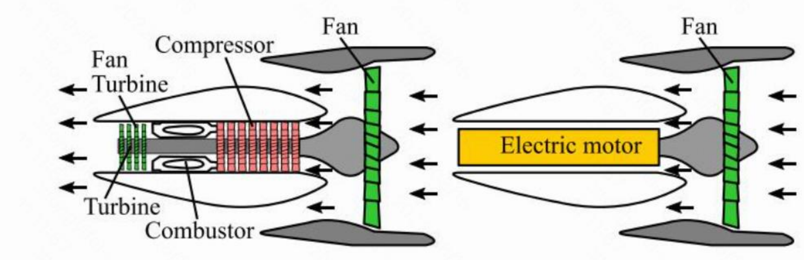

Figure 5. The structure of Turbofan engine [10]

To measure the performance of a propulsion system, one vital concept named bypass ratio should be delivered at first. The value of bypass ratio is described as followed. In this formula m_o represents the mass of air which flows around the core, while m_i represents the mass of inside flowing air [11].

$$P_{b-p} = \frac{m_o}{m_i} \tag{1}$$

Electrified turbofan propulsion has higher bypass ratio compared with previous gas turbine system, providing a lower exhaust speed which resulting in fuel efficiency enhancement. The functioning noise also decreases. Another advantage is that the turbine is separated with fan in this design, thus the turbine in low pressure can operate at higher speed with the generator, giving an increase on the power density. This structure also can be easily adjusted to suit the distributed propulsion mode, by applying a series of small propulsors, the system can even reach a higher energy efficiency and stability [5]. To operate a totally different energy transmission paths in distributed mode, the necessary redesign for the aircraft EPS is also a research highlight. Figure 6 compares the difference between centralized propulsion and distributed propulsion.

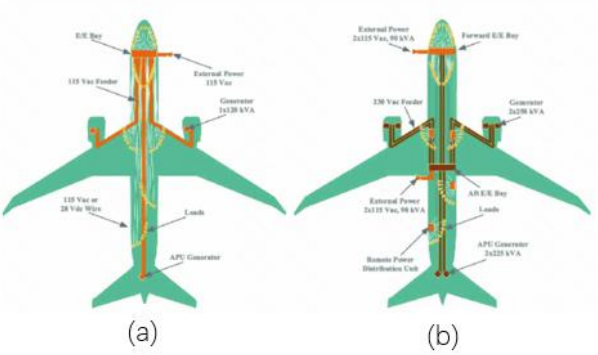

Figure 6. Propulsion modes: (a) Centralized propulsion (b) distributed propulsion [5]

2.4. Environmental control system / Fuel pump

In order to ensure the stability of oxygen content and air pressure in the cabin, the environmental control system of the aircraft must always maintain stable operation. MEA generally has at least two sets of air conditioning systems, and each air conditioning system is equipped with one or two electric driven air compressors. Two permanent magnet electric motors are applied to provide the necessary energy output, with each motor 100-125kVA power consumption [7]. The heated compressed air is mixed with the recirculated air from the cabin and transported back after reaching the set appropriate temperature. A typical structure is shown in Figure 7. The Since MEA has more electronic structures and an updated power distribution system compared with traditional aircraft, the motors that provide power for the environmental control system will also be connected to the main system, thus a more reliable monitoring function can decrease the possibility of cabin-leakage [12].

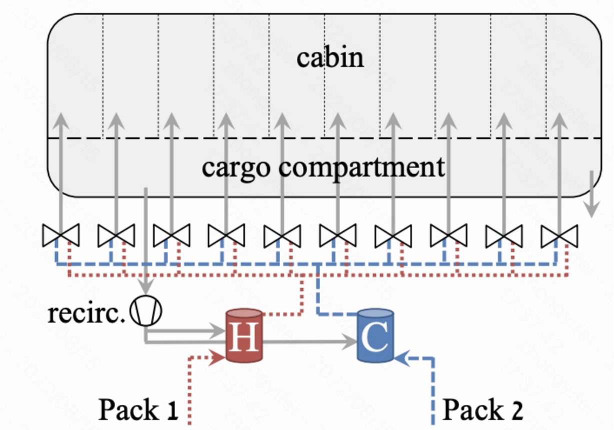

Figure 7. A design for environmental control system [12]

For the fuel pump, traditional structure is to use a mechanically driven high-pressure pump to deliver fuel to the engine, and the size of the high-pressure pump is fixed according to the consumption when the engine is started. If the amount of fuel supplied is greater than the current consumption, the fuel will be returned to the inlet of the pump. When the aircraft is flying in cruise mode, this will cause nearly double the fuel waste. MEA is updated with electrified fuel pump, which can adjust the fuel input according to the engine operation status, which can greatly improve the fuel efficiency [5].

3. Challenges for AEA

3.1. Electrical energy density

Different from MEA which aims to update the electrification level for traditional aircraft, the designed objective for AEA is to remove all forms of energy supply other than electrical energy. Therefore, the study on AEA encountered complex and generational technical barriers. One critical issue is the use of batteries instead of aviation fuel to provide flight power. Aircraft using aviation fuel will gradually consume this part of weight during a flight, but the weight of the battery in AEA is almost constant. This feature requires a reduced battery mass on the aircraft while providing sufficient power [13]. Current research shows that the energy density of all kinds of batteries is far less than that of aviation fuel, including conventional chemical cells, fuel cells and supercapacitors. The specific energy for batteries and their cycle life is listed in Table 1.

Table 1. Comparison of Batteries, Super Capacitors and Fuel Cells. [2]

Technology	Specific Energy (Wh/kg)		Cycle Life(number)	
	State-of-the-art	Future projection	State-of-the-art	Future projection
Ni-Cd battery	50-60	-	2000-2500	-
Li-ion battery	100-265	450	>300	400-450
Li-S battery	250-300	800-950	-	
Li-air battery	300-350	1300-1600	>50	
Supercapacitor	5-15	200-300	∞	∞
Fuel cell	100*	500*	-	

*Specific power (W/kg)

The specific energy for aviation fuel is 2000Wh/kg, that is an overwhelming quantity for nowadays electrical energy sources. Multiple technical breakthroughs are necessary to make AEA a reality, which include improvements on energy storage and battery energy density. Lithium-ion battery is a mature mobile power supply since it has been put into use in the 1990s, but recent research has proved its limitation, therefore other battery structures need to be applied for higher energy density, such as Li-S battery and Li-air battery. These batteries have the characteristics of light weight and low cost of lithium-ion batteries and a greater developing space. At present, their specific energy has been close to the 800Wh/kg demand of hybrid-power aircraft and is expected to be raised to the level required by AEA within 30 years [2].

Fuel cell will be discussed independently of chemical cell because of its special energy supply mode. Fuel cells commonly used in the aviation industry include proton exchange membrane and solid oxide. It is worth noting that if the carbon oxide fuel is used, the exhaust gas will still contain the greenhouse gas carbon dioxide, and the emission is almost close to the combustion of aviation fuel. Instead, the application of hydrogen can achieve environmental protection. But the issue for hydrogen is that its flammability means any spark discharge may lead to gas explosion, which puts forward extremely stringent requirements for the stability of the system [14]. Moreover, the specific energy for fuel cell is slightly higher than traditional Li-ion battery, but lower than Li-S battery and Li-air battery. That makes the fuel cell only suitable as the energy source in the cruise phase or the emergency standby energy, since it cannot provide the high power in the takeoff and landing phases of the aircraft.

3.2. EMI effects

Electromagnetic interference (EMI) has always been an important consideration in the design of aircraft. Even small-scale electronic devices, such as mobile phones, laptops and electronic toys, may affect the radio and radar signals of aircraft, resulting in yaw of cruise systems and unstable display of flight parameters. Rare lightning and solar flares can cause more severe system anomalies. These are called external EMI since they are produced by the sources outside aircraft structure. In contrast, the internal EMI refers to the system abnormality caused by the electromagnetic radiation generated inside the electronic components of the aircraft. These two different EMI categories are schematically shown in Figure 8.

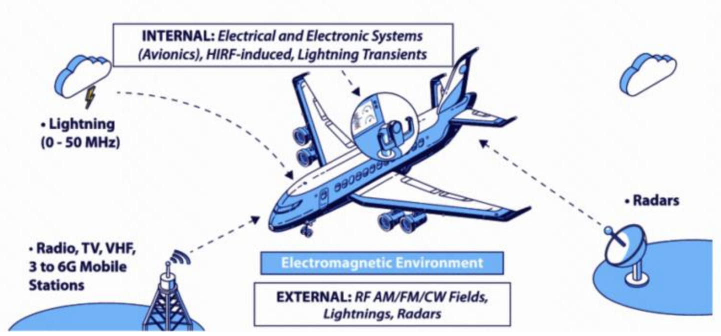

Figure 8. The external/internal EMI [15]

The methods to control EMI in traditional aircrafts include shield termination, wiring classification and device shielding. However, in line with the changing electromagnetic environment on AEA, more powerful EMI will occur as a result of complicated electrical systems' interaction. The electrified power system should be considered first since it provides extremely high power in the take-off stage, which inevitably produces high-intensity electromagnetic radiation [15]. In the design of power system, two typical types of motor are induction motor (IM) and permanent magnet synchronous motor (PMSM). However, regardless of the type of motor used, the windings of the motors in different operating states of the aircraft will undergo power variations when the operating mode is switched. This transient voltage and current fluctuation will propagate in the coupling path, affecting all associated electronic devices. Brushless DC motor (BLDC) seems to be a better choice in controlling EMI, although it still encounters the switching interference, its DC structure can avoid the board EMI since it contains less AC paths.

4. Conclusion

The advantages of electrical components in MEA/AEA that update and replace traditional mechanical and hydraulic systems in aircraft are be summarized below:

Reduce the weight due to electrification, resulting in lower energy consumption

More stable and controllable takeoff and landing system due to the electrical taxiing/brake system

Enhance the engine performance by the increase on bypass ratio

Avoid the waste of aviation fuel by applying electrical fuel pump

To actualize AEA, the technical barriers and future development directions are concluded as follows:

Improve the battery energy density to provide adequate take-off and landing power, both chemical cell and fuel cell should be further studied.

Control the strengthened EMI on electrified aircraft by redesigning the wiring paths and applying more effective device shielding.

References

[1] P. Kshirsagar, J. Ewanchuk and M. Kheraluwala, "Next Generation of Robust Aviation Electrification - Challenges and Opportunities," 2021 IEEE International Electron Devices Meeting (IEDM), 31.5.1-31.5.4 (2021).

[2] A. Barzkar and M. Ghassemi, "Components of Electrical Power Systems in More and All-Electric Aircraft: A Review," in IEEE Transactions on Transportation Electrification (2022)

[3] R. Alexander, D. Meyer and J. Wang, "A Comparison of Electric Vehicle Power Systems to Predict Architectures, Voltage Levels, Power Requirements, and Load Characteristics of the Future All-Electric Aircraft," 2018 IEEE Transportation Electrification Conference and Expo (ITEC), 194-200 (2018).

[4] V. E. Kuznetsov, N. D. Khanh and A. N. Lukichev, "System for Synchronizing Forces of Dissimilar Flight Control Actuators with a Common Controller," 2020 XXIII International Conference on Soft Computing and Measurements (SCM), 137-140 (2020).

[5] E. Sayed et al., "Review of Electric Machines in More-/Hybrid-/Turbo-Electric Aircraft," in IEEE Transactions on Transportation Electrification 7(4), 2976-3005 (2021).

[6] P. Giangrande, A. Al-Timimy, A. Galassini, S. Papadopoulos, M. Degano and M. Galea, "Design of PMSM for EMA Employed in Secondary Flight Control Systems," 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), 1-6 (2018).

[7] J. Bae, "A Review of Electric Actuation and Flight Control System for More/All Electric Aircraft," 2021 24th International Conference on Electrical Machines and Systems (ICEMS), 1943-1947 (2021).

[8] M. Lukic, P. Giangrande, A. Hebala, S. Nuzzo, and M. Galea, “Review, challenges, and future developments of electric taxiing systems,” IEEE Trans. Transport. Electrific. 5(4), 1441-1457 (2019).

[9] D. Rohacs and J. Rohacs, “Magnetic levitation assisted aircraft take- off and landing (feasibility study-Gabriel concept),” Prog. Aerosp. Sci. 85, 33-50 (2016).

[10] [10] P. J. Masson, J. E. Pienkos, and C. A. Luongo, “Scaling up of HTS motor based on trapped flux and flux concentration for large aircraft propulsion,” IEEE Trans. Appl. Supercond. 17(2), 1579–1582 (2007).

[11] C. A. Luongo et al., “Next generation more-electric aircraft: A potential application for HTS superconductors,” IEEE Trans. Appl. Supercond. 19(3), 1055–1068 (2009).

[12] A. Pollok, "Control strategies for an advanced aircraft-cabin temperature-system," 2017 IEEE Conference on Control Technology and Applications (CCTA), 2138-2143 (2017).

[13] P. Wheeler, "Technology for the more and all electric aircraft of the future," 2016 IEEE International Conference on Automatica (ICA-ACCA), 1-5 (2016).

[14] S. V. M. Guaitolini, I. Yahyaoui, J. F. Fardin, L. F. Encarnação and F. Tadeo, "A review of fuel cell and energy cogeneration technologies," 2018 9th International Renewable Energy Congress (IREC), 1-6 (2018).

[15] L. Malburg, N. Moonen and F. Leferink, "The Changing Electromagnetic Environment Onboard All-Electric Aircraft, an EMC Perspective," 2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium, 845-850 (2021).