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Improving maintainability of the Battery Storage System in Electric Aircrafts

Ashrith Jain[a,b*], Alberto Martinetti[a], Leo van Dongen[a]

[a]*Design, Production and Management Department, Univerity of Twente, Drinerlolaan 5, Enschede 7522 NB, The Netherlands;*
[b]*DEAC Dutch Electric Aviation Centre Teuge, De Zanden 13B, Teuge 7395 PA, The Netherlands*

* Corresponding author. Tel.: +31-53-489-2884; *E-mail address:* a.jain-1@utwente.nl

Abstract

Due to the rising environmental awareness and fluctuating fuel prices over the past decade, several countries started collaborating on a national program to achieve the climate agreement goals of the Paris agreement. At the moment, one of the most crucial challenges of the electrification process is the replacement of conventional engines. As there is a substantial gap in energy density between fuel and batteries per unit volume, the consequence is increasing aircraft weight after electrification. The overall stability and configuration of the aircraft are affected by the altered weight, hence requiring further analysis. This paper focuses on discussing and proposing future solutions for the battery storage system in terms of maintainability and position in the aircraft. Methodology-wise, to validate the research solutions the paper uses a conventional aircraft planned to be retrofitted with a hybrid propulsion system as a case study. The results show that the battery system has to be separated into two main categories, namely the energy and structural storage system where the former concerns the selection of battery type and defining the battery size/ weight based on the required energy output and whereas the latter regards the positioning and structural design of the battery storage system.

Keywords: Electric Aviation; Design for Maintenance; Maintainability; Batteries;

1. Introduction

The aviation industry in general is important for the socio-economic development of many countries and has a higher expected growth in comparison with other industries, which is around 5% annually until 2030 [1-3]. However, it has high resilience to liquid fossil fuel, which releases various types of greenhouse gases[1]. The emissions from the aviation industry have grown at an annual rate of 2.2% between 1980 and 2015[4]. There is an urgent need for decarbonization due to rising emissions and concerns over climate change. The Paris agreement aims to maintain the increase of temperature well below 2°C, preferably 1.5°C to avoid dangerous climate change[5]. Also, there are concerns over the depletion of fossil fuels and rising fuel prices [6]. These concerns coupled with obligations are encouraging the aviation industry to transition towards more sustainable aviation and there is a growing interest in the design, development and certification of electrically powered aircraft [7]. Karpuk et al. [8] made an overview of recent research and developments in the field of electric aviation, highlighting projects involving simulation techniques, the effect of hybrid electric aircraft from the operational perspective, distributed electric propulsion (DEP) energy networks, multiple aircraft's concepts, both new and retrofitted that included some of the examples such as retrofitting of Extra 300 aerobatic by siemens, world's first certified all-electric aircraft Pipistrel Velvis Electro and electrified 208B Cessna Grand Caravan.

Battery technology is identified to be the most critical component for the success of Fully Electric Aircraft (FEA) or Hybrid Electric Aircraft (HEA)[9]. Aircraft is much too sensitive to mass, and limited battery energy density, travel range, increased mass, and safety standards pose a hurdle in the development of electric propulsion system concepts[6]. High-powered batteries, in particular, poses both maintenance and safety challenges and it requires new training for the maintenance operators[7]. Currently, a lot of attention is being paid to the concept development and technical feasibility of electric aircraft but there is a gap in the future maintenance knowledge[7]. The design of a system has a greater influence on the maintenance during later stages of the life cycle. As a large part of the life cycle cost is spent on the maintenance of the system, the Design for Maintenance (DfM) approach is crucial to increase availability and reduce the life cycle cost. Maintainability, reliability, and supportability are the key attributes of the DfM approach and influence the overall cost effectiveness[10]. From the maintainability perspective, the battery system can be divided into two main categories, the battery itself and the structural storage system which focuses on the position, structural design, ease of maintenance, and safety. Lack of maintainability leads to higher maintenance costs, and higher repair time, and has an impact on the safety of the maintenance personnel.

Research is being carried out on the design and development of electric aircraft in the Netherlands by different organizations and research institutions with the help of an action program called 'Actieprogramma Hybride Elektrisch Vliegen' (AHEV) by the Dutch government. Dutch Electric Aviation Centre (DEAC) is one of them. It is a knowledge centre based at Teuge International Airport in the Netherlands, working together with companies, educational and research institutions, and governments on the solution for sustainable aviation. Currently, the Cessna Skymaster 337F aircraft is being used as a flying test bed and it is in the process of retrofitting to enable hybrid and electric flying.

In this paper, an overview of the electric propulsion system is made, specifically the battery system. The battery structural storage system is analyzed from the maintainability perspective and using the retrofitting process as a case study, future solutions are proposed.

2. The propulsion system for electric aircraft

Currently, different aircraft concepts are being developed using electric and hybrid-electric propulsion system configurations, which include both new designs and retrofitting processes [8]. They can be classified into three main categories: Hybrid Electric Aircraft(HEA), Full Electric Aircraft(FEA), and Turbo Electric Aircraft (TEA). These three can be further categorized into series hybrid, parallel hybrid, and series/parallel hybrid within HEA and full turbo-electric and partial turbo-electric within TEA[11]. Considering the currently available battery technology, FEA is suitable for smaller aircraft that require less payload capacity and range as the only energy sources are the batteries as shown in Fig.1. Under the HEA, several aircraft concepts are being developed by integrating engines and batteries with various levels of hybridization as shown in Fig.1. TEA configurations do not rely on the batteries, instead the engines are connected to a generator which provides necessary energy required by the electric motor[11]. However, based on the energy source, the propulsion system of electric aircraft can be broadly classified into a battery-based and fuel cell-based system[6]. According to Sziroczak et al.[12] batteries are one of the key elements that are causing a series of problems in the development of HEA that include low energy density, thermal instability, and limited life. In this paper, the battery-based propulsion system is studied to identify the maintenance and safety challenges and to provide a solution from a maintainability perspective.

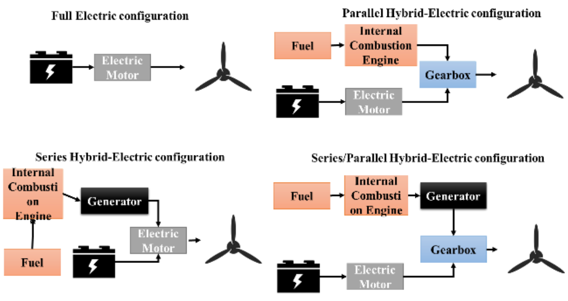

Fig.1. Basic overview of different battery-based propulsion system configurations, inspired by [11, 13]

2.1. Battery-based propulsion system and challenges

Batteries are the key component of an electric aircraft which provide electrical power to drive an electric motor. Battery-powered electric aircraft can operate at 92-96% efficiency in comparison with a combustion engine, whose efficiency range is between 24-50%[12]. However, low specific energy density is hindering the development of electric aircraft to match the performance of aircraft powered by fuel[12]. Currently, the most commonly used battery systems are Lithium-ion types that can provide a mass-specific energy content between 200 to 250 Wh/kg[6]. Battery developers are expecting to achieve specific energy of 750 Wh/kg and above by 2035[12].

High-powered batteries require new inspection, repair protocols, and training for maintenance operators. A study carried out by Naru et al.[7] assessed the concerns of the maintenance operators by performing the task of removing and replacing the batteries. The outcomes of the study revealed that there are concerns over the shock hazards and accidental fouling of the connectors during the battery exchange. The batteries used in electric aircraft operate from 200-800 volts, which poses a safety threat as a single-point failure can lead to accidents[7]. The weight and handling of the batteries pose a challenge to the maintenance operators and the maintenance operators emphasized the need for design for maintainability.[7]

Two key hazards associated with lithium-ion batteries are thermal runaway and energy uncertainty. A thermal runaway is when there is a rapid and uncontrolled increase in the battery temperature leading to the release of toxic fumes, fire, or battery explosion. It can be caused due to over-charging, external heat sources, damage to the physical structure of the battery, manufacturing defects, and maintenance errors. This necessitates the need for a storage system to contain the thermal runway[14]. The operational temperature range of

Lithium-ion batteries is crucial to avoid undesired temperature rises caused by the chemical reaction. SOC influences the energy released in such an event, thus fully charged battery poses a higher risk than a partially charged one. Battery cell design influences the thermal behaviour of Lithium-ion batteries. Cell overheating is the initial condition instigating thermal runway[15]. It happens in three stages: (1) overheating, (2) heat concentration and release of toxic fumes, and (3) potential explosion[15].

During the maintenance operation, safety is of utmost concern. Due to the risk of electrical hazards, toxic fumes, fires, and the possibility of an explosion, maintenance personnel are required to be trained to handle extreme situations and must be equipped with the proper tools and knowledge. Any maintenance error caused during the maintenance operation could pose a hazard to flight safety and the maintenance organization

For this study, the battery system is classified into two main categories, namely the energy and structural storage system. The former concerns the selection of battery type, battery capacity, operational temperature range, charging voltage, and life cycle among other factors to ensure the required power output, avoid thermal runway and enhance the endurance of the aircraft. Whereas the latter regards the positioning and structural design of the battery storage system, which is important to ensure safer and more efficient maintenance.

3. Case study: Retrofitting of Cessna Skymaster 337F by DEAC

DEAC is using Cessna Skymaster 337F as a flying testbed for the electrification process and to study the characteristics of a retrofitted electric aircraft. Conventionally, this testbed has a linear push-pull configuration, with a piston twin-engine, one pushing propellor in the rear and one tractor (pulling) in the front of the aircraft as shown in Fig.2. This configuration ensures that the aircraft does not yaw in case of an engine failure, making it ideal as an experimental aircraft to replace the rear engine with an electric motor powered by batteries. The general characteristics of the test bed are shown in Table.1.

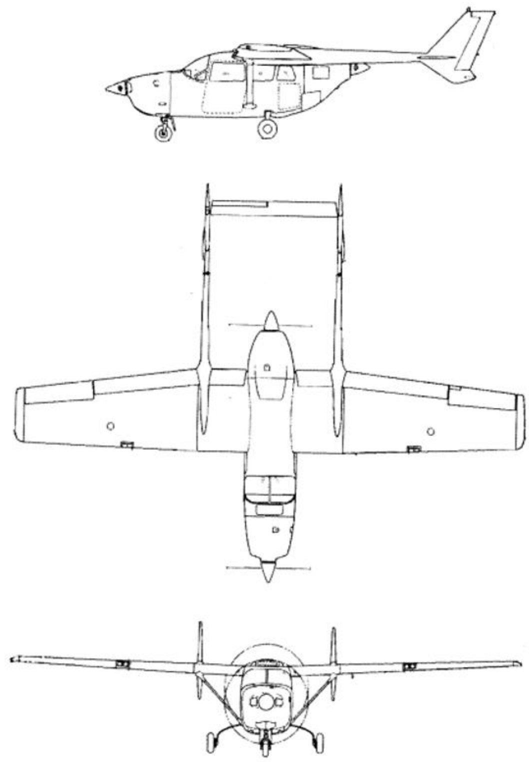

Fig.2. Flying test bed Cessna Skymaster

Table.1. General characteristics of Flying Testbed-Cessna Skymaster 337F, adopted from [16]

Length	9.07 m
Wingspan	11.81 m
Height	2.84 m
Empty weight	1,204 kg
Max. Take off weight	1,996 kg
Powerplant	2 x Continental IO-360-C air-cooled flat-six piston engine, 210 hp (160 kW) each
Propellors	2-bladed McCauley fully-feathering, constant-speed propeller, 1.93 m diameter

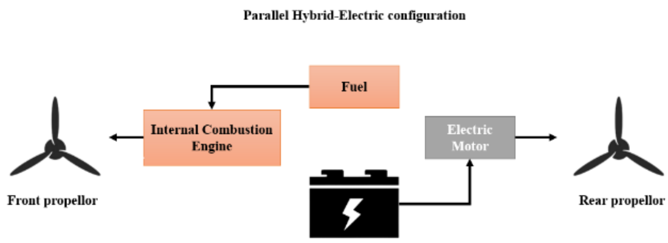

Fig.3. Hybrid-electric propulsion system used in the flying test bed

The electrification process of the test bed will take place in two phases. Phase one will focus on achieving a hybrid propulsion system, where the rear engine will be retrofitted with an electric motor powered by batteries as shown in Fig.3. In the second phase, both rear and front engines will be replaced with an electric motor. Modification of existing aircraft to support electric propulsion systems and fuel cells encompasses a complete rethinking and re-design to facilitate safe and efficient interaction with both aircraft system components and with the airport ecosystems, storage facility, and maintenance organization. As maintenance operations deeply affect both the operability and the financial side of an asset during its lifetime, a Design for Maintenance (DfM) approach should be considered from an early stage in parallel to the development of the system itself.

The battery storage system focuses on the structure that holds the battery modules and how it is attached to the aircraft. During the design of a battery storage system, important aspects to be considered are functionality, maintainability, and safety. Battery positioning should ensure safety, better maintainability, and enable the functionality of the aircraft without affecting the weight distribution and Center of Gravity(CoG). The first step involves battery selection and weight estimation required to provide the required power output, followed by space exploration of the aircraft to identify a potential location for battery placement. Space exploration is influenced by the available free space and COG, as the weight and balance of the aircraft influence the stability, manoeuvrability, and safety during operations. Unlike conventional aircraft that burn fuel during the operation and thus reduce the mass of the aircraft, the weight of the batteries is of concern and must be accounted for during landing weight estimation. Further design for maintainability attributes is incorporated into the design to enable ease of maintenance, focusing on the mechanical structure of the storage system and its attachment to the aircraft itself. Safety design involves the internal design of the storage system to avoid the propagation of fire from one battery module to another. The aim is to achieve an optimum solution by making necessary trade-offs as shown in Fig.4.

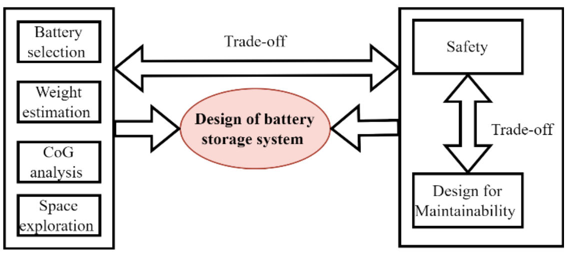

Fig.4. Design of battery storage system during the retrofitting process

4. Design for Maintainability Solutions: Battery storage system

DfM method focuses on achieving a high degree of maintainability, reliability, and support, which affects the availability of the aircraft and in turn helps in reducing the overall life cycle cost. A lack of maintainability can result in higher product maintenance costs, long out-of-service times, and possible injuries to maintenance personnel. Mulder et al. [10] have proposed a set of DfM guidelines, which are used as a preliminary source to formulate solutions.

To retrofit the flying test bed and convert it into a hybrid-electric aircraft and support the rear electric motor, possible locations available for the positioning of the batteries are in the wings by partial replacement of the fuel tanks, back of the fuselage, or an additional belly-pod. However, the additional belly pod is not considered due to safety concerns related to the possibility of batteries catching fire in an event of a crash landing in case of an emergency, the influence of aerodynamics, and load-bearing capacity. Storing the batteries in the wings within the battery storage system can isolate the batteries from the passengers, which is good in terms of safety. Redesign of the fuselage is avoided as it influences the aerodynamics of the aircraft. It also ensures the utilization of the available space and eliminates further structural re-design, analysis, and certification. Further, CoG analysis must be performed to identify the static and dynamic stability range within the selected positions.

Accessibility is the relative ease at which the equipment and its sub-assemblies can be reached for service, replacement, or repair. Ineffective maintenance is often associated with a lack of accessibility. There should be enough space for the components, tools, and safe human-to-machine interaction. The impact of accessibility on repair time, safety, and ergonomics issues concerning maintenance are well known. Assembly/disassembly is one more important aspect to be considered to enable better maintenance operations along with accessibility. It can be achieved by ensuring the easy opening of the battery storage system and surrounding subcomponents. The battery storage system must be designed to enable these aspects.

From an Ergonomics perspective, it is advisable to make the battery storage system more modular so that the maintenance operators can handle the batteries without having to twist the body or apply load on the back. Also to avoid being lifted from a large vertical and horizontal distance. From the maintenance perspective, it is preferable to have a single compact system rather than distributed subsystem. However, having a single compact system can lead to system disruption in an event of failure and cause a serious safety hazard. A trade-off must be done based on further analysis.

The number of cables and their length must be reduced to improve maintainability. The back of the cockpit would be the ideal location for the batteries as it is closer to a rear electric motor. However, to enhance system reliability and safety, overly complex cabling must be avoided as it can overload the system and lead to a potential fire. By using a decentralized/modular Battery Management System (BMS), the cable length can be reduced.

Proper storage of lithium batteries within the storage system is important because they pose a risk of explosion, self-sustaining fire, and emitting toxic gases. Storage requirements vary by the battery manufacturer. These requirements typically include a specific SOC percentage and a temperature range for storage. In addition, the storage system should be connected to the BMS to minimise discharge over time and extends battery life. During the maintenance operations, the battery storage system must be stored in a temperature-controlled room to maintain a temperature specified by the battery manufacturer.

During the design phase, it is important to understand and incorporate maintenance safety. As electric aircraft operate under high voltage, any short circuit of electrical faults can lead to the fatality of the operator or maintenance personnel. It is best to over-design the safety of the storage system to avoid any hazard caused due to negligence. One of the solutions is to provide an isolation monitoring device.

One of the critical parameters in the battery storage system is the cooling system. The selection of the coolant must be based on the operational conditions, temperature, and battery specifications. To achieve the proper cooling effect, battery cells must be placed adjacent to a cooling line. From a maintainability perspective, it is ideal to connect all of the battery modules to the same cooling lines.

As the thermal runway is one of the major concerns during the design, thermal insulation must be provided that can withstand higher temperatures for a longer period in case of failure. However, to reduce overall mass and for better space utilization, the insulation material should not occupy a lot of space within the storage system. Further, the storage system should be made modular to provide spacing between the batteries to prevent fire propagation in case of failure.

During the maintenance operation, non-conductive tooling can be used to avoid any electrical hazard and protect the maintenance personnel from potential electrical shock as it is not desired to always disconnect the batteries during certain maintenance tasks and it is not possible to short the batteries to provide a voltage neutral workspace. From a maintainability perspective, the storage system must be designed to avoid direct contact as much as possible during the inspection.

5. Conclusion

As said, currently, the aviation industry is moving towards sustainability due to concerns over climate change, pollution, and mounting pressure from the government. Several aircraft concepts are being researched and developed, including both new aircraft designs and retrofitting existing aircraft with electric propulsion. One of the key elements of an electric aircraft is the battery system, which is currently being

The paper aimed to have an overview of different electric aircraft configurations. The battery-based propulsion system is studied to understand the maintenance and safety challenges arising from its application in an aircraft. Batteries used in electric aircraft tend to deliver high voltage and require new inspection, repair protocols, and training of the maintenance operators. During the maintenance, the weight and position of the battery affect the handling during maintenance operation and the safety of the maintenance operators. The battery system was classified into two main categories. However, only the battery structural storage system is discussed in the study, including positioning and structural design.

The paper used a the Cessna Skymaster 337F aircraft, owned by the DEAC as a case study to understand the retrofitting process and propose solutions for the battery storage system in terms of maintainability. The aircraft is being converted into a hybrid electric aircraft by replacing the rear engine with an electric motor to be powered by the batteries. During the design of the battery storage system, important factors to be considered are functionality, maintainability and safety. Before the design, the requirements are based on the battery selection, weight distribution, space exploration, and CoG analysis. During the design, maintainability guidelines and safety features are included. To achieve an optimal solution, trade-offs must be done between these factors.

Possible locations for the battery storage system were identified to be at the back of the fuselage, close to the electric motor, and in the wings by partial replacement of the batteries. Important maintainability attributes that influences the maintenance operators are accessibility, assembly/disassembly, ergonomics, and maintenance safety.

The paper offered an overview of the battery storage system. However, a detailed design of the solution and structural and thermal analysis by simulations with thorough static and dynamic stability calculations to support the proposed design solutions is still required. As the retrofitting process is in the early design phase, the design solutions must be tested and verified for maintenance operations using an Immersive Virtual Evaluation and Verification Method by carrying out maintenance operations in a virtual environment.

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