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A method to improve the efficiency of an electric aircraft propulsion system

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ABSTRACT

An electric aircraft propulsion system utilizes a high efficiency motor to generate thrust for electric aircraft. However, it can be challenging to maintain high efficiency for the fixed pitch propeller, which is commonly used in electric aircraft, through all phases of the flight. This paper investigates the power demands of the electric aircraft during the climb and the cruise phases according to the flight profile, and presents a model to estimate the energy consumption per flight. Simulation results suggest that the efficiency in the climb and the cruise phases can affect the energy consumption of an electric aircraft. Efficiency during the climb phase can have a significant effect on the capacity of the electric aircraft propulsion system. Based on the aforementioned results, this paper proposes a novel approach to achieve high efficiency, in which the optimal efficiency points of the electric aircraft propulsion system in the climb and the cruise phases can be obtained by solving an optimization problem with minimizing the energy consumption per flight as the object function and under the constraints that the climb and cruise phases must be successful. For testing purposes, the proposed method is adopted to the design of the electric aircraft propulsion system on a specific two-seater electric aircraft. Experimental results obtained from real flights suggest that the proposed method can reduce the energy consumption of the electric aircraft by over 10%, while reducing the capacity demand for the electric aircraft propulsion system.

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1. Introduction

The electric aircraft is an environment-friendly aircraft in terms of cost, efficiency, safety and environmental protection [1]; therefore, many countries such as Europe, USA and China have been developing electric aircraft [2]. Nowadays, a variety of electric aircraft including electric model aircraft, electric unmanned aircraft and electric rotor aircraft, as well as electric glider, serve many fields including industrial production, agriculture, forestry, animal husbandry, education, entertainment [3]. However, there are still many unresolved issues for developing electric aircrafts [4].

The batteries are the power source of an electric aircraft [5]. Due to the limitation of battery energy-density, only a few types of batteries can be applied to electric aircrafts [6]. So far, three types of batteries: lithium batteries, air/metal batteries and graphene batteries are believed to be suitable for electric aircraft [7]. However, air/metal batteries and graphene batteries are still in the research stage [8]; therefore, only lithium batteries have been applied to electric aircraft. Although the energy density of lithium batteries can theoretically reach 300 W·h/kg [9], the actual practical capacity is much lower to satisfy the structure requirement [10]. For a two-seater electric aircraft, its power demand is about 20 kW during the cruise phase, and the weight of its equipped batteries is less than 100 kg [11]. In addition, given the limited batteries life, which is usually less than 1 h, the power demand during take-off, climbing and landing phases has to be taken into consideration as well [12].

To design high performance electric aircraft propulsion system (EAPS) for electric aircraft and to improve the endurance of electric aircraft, improvements must be made, such as choosing the motor with higher power and lighter weight [13]. Currently, there is still little research on improving the efficiency of the EAPS of electric aircraft and the EAPS is not utilized properly to fulfill its potential [14].

The EAPS generates the thrust for an electric aircraft. An EAPS consists of a controller, a permanent magnet synchronous machine (PMSM), a propeller and a set of batteries [15]. The PMSM and the

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controller have a wide high-efficiency operation range. In comparison, the fixed pitch propeller, which is usually used on a small-size electric aircraft, has very limited operation range to achieve high efficiency throughout entire flight [16]. As the result, the propeller usually operates at its peak efficiency during the cruise phase to reduce the overall energy consumption [17].

However, peak efficiency during the cruise phase does not guarantee that the EAPS will be operating at high efficiency during climbing phase. The climbing phase demands large amount of power, which is at least 2.5 times of the power required in the cruise phase [18]; therefore, the capacity of the EAPS must take consideration of the power demand during the climb phase. Low efficiency during the climb phase results in additional capacity requirement for the EAPS, which increase the weight of the EAPS and by extension, increase the energy consumption [19].

This paper presents a novel approach to improve the efficiency of the EAPS. The power demands of an electric aircraft during the climb and the cruise phases, as well as the efficiency of the EAPS are analyzed. The best efficiency points of the EAPS during the climb and the cruise phases can be obtained by optimizing its energy consumption. The method presented in this paper is used to design the EAPS for manned electric aircraft. Experimental results show that the proposed method can effectively reduce the energy consumption of the EAPS and increase the battery-life of the electric aircraft [20].

The rest of this paper is organized as following: Section 2 discusses the energy consumption of the EAPS in different flight phases. The proposed method to achieve the best efficiency points of the EAPS is introduced in section 3. Section 4 presents experiments results obtained from the real flight tests. Section 5 presents the conclusion of this paper.

2. Energy consumption of EAPS

2.1. Flight profile of electric aircraft

The flight profile of an electric aircraft is shown in Fig. 1, which can be separated into four phases: take-off (from 0 to 1 min), climbing (from 1 min to 4 min), cruising (from 4 min to 34 min) and landing (from 34 min to 38 min). Energy consumption varies from phase to phase. For instance, the take-off phase requires similar power output to the cruise phase. However, it only contributes to less than 2% of the total energy consumption due to its short interval (usually around 1 min). The climb phase, which usually last for 3 min, constitutes about 20% of the total energy consumption and its power requirement is 2.5 times of the cruise phase power. Despite of its relative lower power requirement comparing to the climb phase, the cruise phase still makes up more than 75% of the total energy consumption for flights over 30 min. The landing phase consumes the least amount of energy at about 0.5% of the total energy consumption. Its power requirement is 40% of the cruise phase power. It can be concluded that, the take-off and landing phases combined are less than 2.5% of the total energy consumed due to their low power requirement and short operation time. Considering the limited impact from the take-off and the landing phases, the proposed model for analyzing power and energy consumption only involves the climb and the cruise phases [21].

2.2. Principle of EAPS

Unlike airplanes powered by internal combustion engines, an electric aircraft is powered by the EAPS. As shown in Fig. 2, the EAPS consists of the following components: the controller (which has a drive module and a control module), the motor, the power batteries, the user interface (power integrated display), the throttle stick, the auxiliary power and other miscellaneous components. During the flight, the pilot in the aircraft cockpit controls the throttle lever, which outputs an analog signal to the control module of the controller. The control module adjusts the output of the drive module according to the analog quantity. The drive module of the controller converts direct current (DC) supplied by the power batteries into alternating current (AC) to drive the motor and the motor rotates the propeller to generate thrust for the airplane. The power batteries are fully charged and installed before the flight and removed from the airplane for charging after the flight. Usually, an electric aircraft is equipped with two or more rechargeable batteries to guarantee sufficient energy. Batteries recharged more than 800 times or containing less than 85% of initial capacity are removed from service and recycled. The pilot can obtain information about the status of the motor, the controller, and the power batteries through the power integrated display on the front panel. The power integrated display and the control module of the controller are powered by a 24VDC lithium battery [22].

2.3. Energy consumption of EAPS

As mentioned in section 2.1, the climb and the cruise phases contributes to more than 95% of the total energy consumption. The other two phases are ignored for now [23].

The power requirement for climbing and cruise is determined by the propeller, which can be calculated as the product of the thrust of the propeller and the aircraft velocity. i.e.

$$P_{pro} = T_{pro} \cdot v \tag{1}$$

where, T_{pro} is the thrust generated by the propeller and v is the

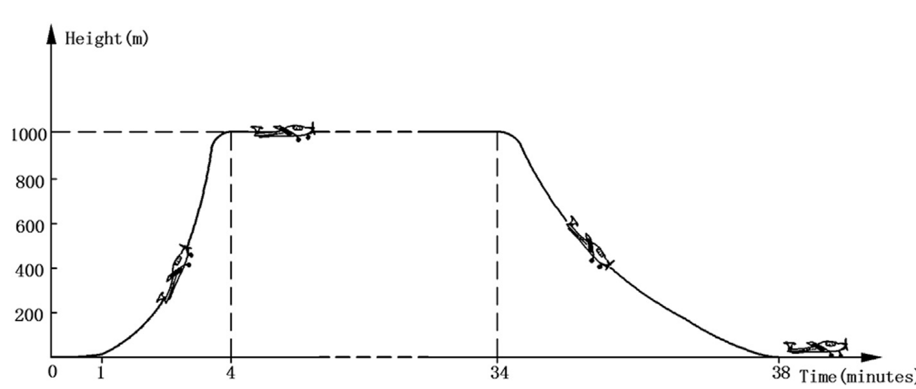

Fig. 1. Flight profile of electric aircraft.

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