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An Energy Efficiency Optimization Method for Fixed Pitch Propeller Electric Aircraft Propulsion Systems

SHULI WANG[1,2], SHUO ZHANG[3], AND SHAOHUA MA[1]

[1]School of Electrical Engineering, Shenyang University of Technology, Shenyang 110023, China
[2]Key Laboratory of General Aviation, Shenyang Aerospace University, Shenyang 110136, China
[3]National Engineering Laboratory for Electric Vehicles, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

Corresponding author: Shaohua Ma (mash_dq@sut.edu.cn)

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ABSTRACT As a key component of electric aircrafts, electric propulsion systems provide sufficient thrust for electric aircrafts. By improving its efficiency, the power consumed by the electric propulsion system can be reduced. Therefore, the maximum range of electric aircrafts, which is limited by the energy density of batteries, can be further increased. Upon investigating the power demand and the energy consumption of the electric propulsion system in each flight profile phase of fixed pitch propellers electric aircrafts, this paper proposes a novel energy efficiency optimization method tailored for fixed pitch propeller electric aircrafts by minimizing the total energy consumption of one flight over the maximum efficiency of the propeller. The proposed method is adopted to the design of a fixed pitch propeller electric aircraft. Experimental results suggest that the tested fixed propeller electric aircraft designed can achieve better energy efficiency while reducing energy consumption by more than 10%.

INDEX TERMS Electric aircrafts, electric propulsion system, energy efficiency optimization, system energy consumption.

I. INTRODUCTION

Electric aircrafts are powered by rechargeable batteries and driven by electric propulsion systems instead of internal combustion engine. Compared to fuel powered aircrafts, electric aircraft have more advantages including low-carbon emissions, low noise level, simple maintenance, etc. [1]. Despite the fact that many nations have been developing electric aircrafts; some major problems have yet to be solved [2]. One of the major problems is that the maximum range of electrical aircrafts is limited, can only meets minimum requirement [3].

One of the most efficient methods to improve the maximum range is to reduce the energy consumption of electric propulsion systems [4]. Many researches on optimizing the energy consumption of electric propulsion systems have been focused on optimized control over three major components of electric propulsion systems, which are, electric motor, controller and propeller. C. E. Jones et al proposes a pre-design sensitivity analysis tool for electric propulsion system of full electric aircraft, which offers significant reduction of the electrical losses in the electric propulsion systems [5]. G. W. Kang et al put forward a method of parameter matching of electric propulsion system for a certain ultra-light electric aircraft. The motor, controller, propeller and battery are selected on the basis of the requirements of aircraft design parameters. The electric propulsion system was constructed and applied to electric aircraft. However, this method does not optimize the energy consumption of electric propulsion system. [6]. S. H. Ma et al put forward a method to improve the efficiency of an electric aircraft propulsion system via a model which is established according to the operating conditions of aircraft. However, the description of the optimization method is not detailed enough [7]. B. Mecrow et al applied a modified adaptive variable step incremental algorithm to the propulsion system of solar powered electric aircrafts [8]. J.C. Bentz improved electric propulsion unit's efficiency by matching fuel cell powered HALE aircraft's propulsion system [9]. G. Romeo et al. designed a highly efficient battery system [10]. J. F. Guerreiro et al. Optimized the electric propulsion system using active power filter [11].

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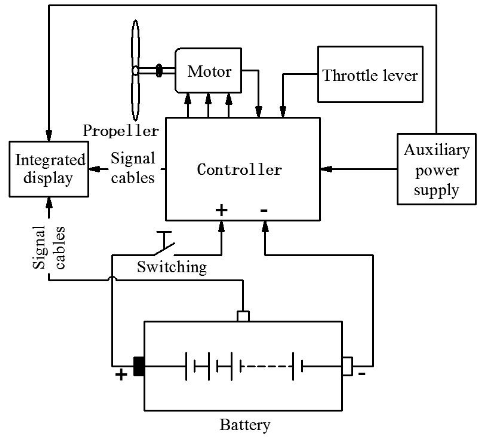
K. Takahashi et al. proposed a two-quadrant thrust control method for electric propulsion systems [12]. N. Konishi et al. proposed a control system based on thrust distribution optimization [13]. P. J. Masson used High Power Density Superconducting Motor in electric aircraft's EPU, the weight of EPU had been reduced and system efficiency of EPU had been improved [14]. These methods are capable of reducing the energy consumption of electric propulsion systems and improving the maximum flying range by increasing the operating efficiency and widening the high efficiency operating range of controllers and motors.

Fixed pitch propellers are most commonly used for small electric aircrafts. Fixed pitch propellers have narrow high efficiency operating range. Besides, the efficiency of fixed pitch propellers cannot be controlled adaptively according to the flight profile [15]. Therefore, it is difficult to maintain high efficiency through the entire flight for fixed pitch propeller electric aircrafts. This paper investigates the power demand of lightweight aircrafts during different phases of the flight profile and presents a method to minimize energy consumption by optimizing the peak efficiency operating point of the propeller. The proposed method is adapted to the design of the propulsion system of a lightweight electric aircraft. Experimental result gained from flight test suggests that the proposed method can effectively improve the efficiency of the propulsion system, can reduce the overall energy consumption by more than 10%.



(a) Composition of the propulsion system

(b) Aircraft seat

FIGURE 1. Composition of the propulsion system and the aircraft seat.

II. EFFICIENCY AND ENERGY CONSUMPTION OF ELECTRIC PROPULSION SYSTEMS

A. COMPONENTS OF ELECTRIC PROPULSION SYSTEMS

There are following major components to electric propulsion systems: the motor, the controller, the propeller, the battery, the integrated display, the throttle lever, and the auxiliary power supply. The controller converts dc voltage generated by the battery to 3-phase ac voltage to drive the motor [16]. The motor drives the propeller to generate thrust for the aircraft. The speed of the propeller can be adjusted through the throttle lever, which is controlled by the pilot. The integrated display shows the operating status of the motor, the controller and the battery. The integrated display and the controller are powered by the auxiliary power supply. The battery needs to be charged. The battery can only be charged using the charging device, and it has to be taken out from the aircraft to charge. The battery has limited charge cycles. As shown in Figure 1, the propeller provides thrust for the aircraft; the propeller is driven by the electric motor; the motor is controlled by the controller and the electric propulsion system is powered by the battery.

B. EFFICIENCY OF ELECTRIC PROPULSION SYSTEMS

The power of an electric propulsion system is related to its efficiency and the power of the aircraft:

$$P_{\mathrm{es}} = \frac{P_{\mathrm{plane}}}{\eta}, \tag{1}$$

where P_{es} is the power consumption of the electric propulsion system, P_{plane} is the power consumption of the plane and η is the efficiency of the electric propulsion system. The efficiency of an electric propulsion system, η, is determined by the efficiency of the propeller η_{pr}, the efficiency of the electric motor η_{mo}, and the efficiency of the controller η_{co}:

$$\eta = \eta_{mo} \cdot \eta_{co} \cdot \eta_{pr} \tag{2}$$

High efficiency range of permanent-magnet synchronous motors (PMSM) and controllers are wide. Therefore, the motor and the controller can operate at high efficiency during the take-off and the cruise phase. On the other hand, fixed pitch propellers have limited high efficiency range and cannot be adjusted adaptively [17].

The efficiency of a fixed pitch propeller follows the set of equations below:

$$\begin{cases} \lambda = \dfrac{60 v_{\mathrm{fl}}}{n_s R_{\mathrm{pr}}} \\ C_T = \dfrac{T}{\rho n_s^2 R_{\mathrm{pr}}^4} \\ C_W = \dfrac{W}{\rho n_s^2 R_{\mathrm{pr}}^5} \\ \eta_{pr} = \dfrac{C_T \lambda}{C_w} \\ W = 2\pi n_s Q \end{cases} \tag{3}$$

where λ is the advance ratio of the propeller, C_T is the thrust coefficient, C_W is the power coefficient, R_{pr} is the diameter of the propeller, n_s is the rotational speed of the propeller, T is the thrust of the propeller, v_{fl} is the flow velocity, W is the input power, Q is the torque of the propeller.

It can be derived from equation 3 that the efficiency of the propeller is:

$$\eta_{\text{pr}} = \frac{30 v_{\text{fl}} T}{\pi n_s Q} \tag{4}$$

Figure 2 shows the efficiency characteristic curve and the thrust characteristic curve of electric aircrafts. As shown in Figure 2a and Figure 2b, the thrust demand during the takeoff phase is high so that the propeller has to operate at a high rotational speed n_s. During the cruise phase, the thrust demand decreases, and the propeller operates at a lower speed. However, given its narrow high efficiency operating range, the propeller cannot operate at high efficiency during both the takeoff phase and the cruise phase. On the other hand, the controller and the motor, as shown in Figure 2c and Figure 2d, are capable of operating at high efficiency during both phases, whose efficiency can be assumed to be constant.

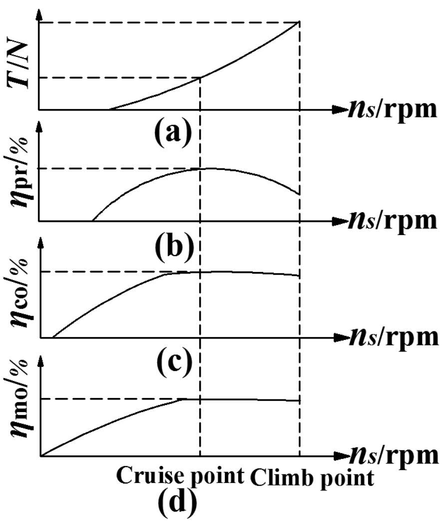


FIGURE 2. Characteristic curve of the propeller, controller and motor.

C. ENERGY CONSUMPTION OF ELECTRIC PROPULSION SYSTEMS

For electric aircrafts, each flight contains four main phases, which are the take-off phase, the climb phase, the cruise phase and the descent phase [18]. Given their short interval and low power demand, the take-off phase and the descent phase only contribute less than 2% of the total energy consumption.

The capacity for the motor and the controller needs to be large enough to satisfy the power demand during the climb phase. For safety purpose, the maximum power output of the propulsion system is determined by the power demand of the climb phase [10]. Power demand during the climb phase is the highest among four phases, which can be approximately 3 to 4 times of the power demand during the cruise phase. Power demand during the climb phase can be calculated as:

$$\begin{cases} a = \dfrac{v_c^2 - v_t^2}{2D_d} \\ A_d = \frac{1}{2}\rho v_c^2 S C_d \\ T_f = A_d + Mg\dfrac{H}{\sqrt{D_d^2 + H^2}} + Ma \\ \rho = 0.0034831 \times A_p \big/ (273.15 + T_e) \\ P_t = T_f \times v_t \\ D_d = \dfrac{1}{2} t_t (v_c + v_t) \\ M = m_{\text{pl}} + m_{\text{pr}} + m_{\text{es}} \end{cases} \tag{5}$$

where ρ is the air density, a is the acceleration during the climb phase, v_c is the cruise velocity, v_t is the unstick speed, D_d is the travel distance (horizontal distance from take-off to cruise), S is the area of the wing, A_d is the aerodynamic resistance, C_d is the aerodynamic resistance coefficient, T_f is the thrust demanded during the climb phase, H is the flight height, m_{pl} is the mass of the aircraft, m_{pr} is the weight of the pilot, m_{es} is the mass of the electric propulsion system, M is the lift-off mass of the aircraft, A_p is the atmosphere pressure, T_e is the atmosphere temperature, P_t is the climb power and t_t is the climb time.

The climb power and time can be derived from equation 5, which are:

$$P_t = (\frac{1}{2}\rho v_c^2 S C_d + Mg\frac{H}{\sqrt{D_d^2 + H^2}} + M\frac{v_c^2 - v_t^2}{2D_d}) \times v_t \tag{6}$$

$$t_t = \frac{2D_d}{v_c + v_t} \tag{7}$$

The power demand of the propulsion system during the climb phase $P_{\text{es\_f}}$ can be derived from equation 1 and equation 6 as:

$$P_{\text{es\_f}} = \frac{v_t(\frac{1}{2}\rho v_c^2 S C_d + Mg\frac{H}{\sqrt{D_d^2+H^2}} + M\frac{v_c^2-v_t^2}{2D_d})}{\eta} \tag{8}$$

Combining equation 2, equation 7 and equation 8, the energy consumption during the climb phase E_{es} can be calculated as:

$$E_{\text{es}} = \frac{2D_d v_t(\frac{1}{2}\rho v_c^2 S C_d + Mg\frac{H}{\sqrt{D_d^2+H^2}} + M\frac{v_c^2-v_t^2}{2D_d})}{\eta_{\text{mo}}\eta_{\text{co}}\eta_{\text{per}}(v_c + v_t)} \tag{9}$$

where η_{per} is the efficiency of the propeller during climb phase. It can be concluded from equation 9 that the energy consumption during takeoff is related to the mass of the aircraft, the unstick speed, the cruise speed, the horizontal travel distance, the wing area, the motor efficiency, the controller efficiency and the efficiency of the propeller. The unstick speed, the cruise speed, the horizontal travel distance and the wing area can be considered as constants. Therefore, energy consumed during the climb phase is proportional to the mass of the aircraft, and inversely proportional to the efficiency of the controller, the motor and the propeller. Given the fact that the motor and the controller are operating at high efficiency during the climb phase, their impact to the energy consumption of the propulsion system can be ignored [19].

The power of the propulsion system during the cruise phase P_{cr} is:

$$P_{\mathrm{cr}} = T_{\mathrm{cr}} v_c \tag{10}$$

where T_{cr} is the thrust of the aircraft during the cruise, v_c is the cruise speed.

The thrust required during the cruise phase is equal to the resistance it received, therefore:

$$T_{\mathrm{cr}} = \frac{Mg}{L/D_F} \tag{11}$$

where, L/D_F is the lift-to-drag ratio of the aircraft. It can be concluded from equation 11 that the thrust generated from the propeller during the cruise phase is only related to the lift-to-drag ratio.

The power demand of the propulsion system during the cruise phase can be derived from equation 10 and equation 11 as:

$$P_{\mathrm{cr}} = \frac{v_c Mg}{\eta} \cdot \frac{1}{L/D_F} \tag{12}$$

As shown in equation 12, the power demand of the propulsion system during the cruise phase is related to its efficiency, the cruise velocity, the mass and the lift-to-drag ratio of the aircraft.

From equation 2 and equation 12, the energy consumed during the cruise phase E_{cr} can be calculated as:

$$E_{\mathrm{cr}} = \frac{v_c Mg}{\eta_{\mathrm{mo}} \eta_{\mathrm{co}} \eta_{\mathrm{pcr}}} \cdot \frac{1}{L/D_F} t_{cr} \tag{13}$$

where t_{cr} is the cruise time, η_{pcr} is the efficiency of the propeller during the cruise phase. It can be concluded from equation 13 that for a given aircraft type, the lift-to-drag ratio and the cruise speed are constants. Consequently, energy consumed by the propulsion system during the cruise phase is inversely proportional to its efficiency and proportional to the mass of aircraft and the cruise time. As the efficiency of the controller and the motor during the cruise phase can be treated as constants, the energy consumption of the propulsion system during the cruise phase is in inverse proportion to the efficiency of the propeller.

III. EFFICIENCY OPTIMIZATION FOR ELECTRIC PROPULSION SYSTEMS

To reduce the energy consumption of the propulsion system and increase its efficiency, this paper presents an optimization method that coordinates each components of the propulsion system to improve its output efficiency. By increasing the efficiency of the propulsion system, the capacity of the propulsion system can be reduced; consequently, reduce the energy consumed per flight [20], [21].

The energy consumption of the take-off and the descent phase can be ignored given their limited contribution to the total energy consumption. According to equation 9 and equation 13, the energy consumed per flight E can be approximated as:

$$E = \frac{2D_d v_t (\frac{1}{2}\rho v_c^2 S C_d + Mg \frac{H}{\sqrt{D_d^2+H^2}} + M\frac{v_c^2 - v_t^2}{2D_d})}{\eta_{\mathrm{mo}} \eta_{\mathrm{co}} \eta_{\mathrm{per}} (v_c + v_t)} + \frac{v_c Mg}{\eta_{\mathrm{mo}} \eta_{\mathrm{co}} \eta_{\mathrm{pcr}}} \cdot \frac{1}{L/D_F} t_{cr} \tag{14}$$

For a given aircraft model, equation 14 can be further simplified as:

$$E = \frac{1}{\eta_{\mathrm{per}}}(k_1 + Mk_2) + \frac{k_3 M}{\eta_{\mathrm{pcr}}} \tag{15}$$

where

$$\begin{cases} k_1 = \dfrac{D_d v_t \rho v_c^2 S C_d}{\eta_{\mathrm{mo}} \eta_{\mathrm{co}} (v_c + v_t)} \\ k_2 = \dfrac{2D_d gH + (v_c^2 - v_t^2)\sqrt{D_d^2 + H^2}}{2D_d \sqrt{D_d^2 + H^2}} \\ k_3 = \dfrac{v_c g D_F t_{\mathrm{cr}}}{L \eta_{\mathrm{mo}} \eta_{\mathrm{co}}} \end{cases} \tag{16}$$

k_1, k_2 and k_3 are all constants.

The optimization objective function of the propulsion system can be derived from equation 5, equation 11 and equation 15 as:

$$\begin{aligned} E_{\mathrm{min}} = \min \left(\frac{1}{\eta_{per}}[k_1 + Mk_2] + \frac{k_3 M}{\eta_{pcr}} \right) \\ sb.\ T_f \geq T_{f\_\mathrm{min}} \\ T_{cr} \geq T_{c\_\mathrm{min}} \end{aligned} \tag{17}$$

where T_{f_min} and T_{c_min} are the minimum thrust demands of the propeller during the climb and cruise phase, E_{min} is the minimum energy consumed according to the flight profile.

Most fixed pitch propellers are designed to operate at peak efficiency during the climb phase or the cruise phase. For propellers that operate at highest efficiency during the climb phase, the propulsion system can operate at high efficiency when climbing, which requires less power. Therefore, the capacity demand of the propulsion system is lowered, and its weight can be reduced. However, due to the limited high efficiency operating range of the propellers, the efficiency during the cruise phase decreases, which raises the power demand, which results in higher total energy consumption per flight [22]. On the other hand, switching the peak operating point of the propellers to the cruise phase could reduce the efficiency of the propulsion system during the climb phase, which increases capacity for the propulsion system for higher power demand, which also leads to higher energy consumption [23]. Therefore, fixed pitch propellers should not be designed to operate at peak efficiency during the climb phase or the cruise phase. This paper presents a novel method that can determine the optimum peak efficiency operating point of the propeller by optimizing the overall energy consumption over the rotational speed of the propeller. The proposed method can effectively improve the efficiency of the propulsion system and reduce the energy consumption. The proposed method is adopted to the design of an electric aircraft. Experimental result obtained from ground test indicates that the optimum peak efficiency operating point determined by the proposed method can indeed minimize overall energy consumption.

A. ENERGY EFFICIENCY OPTIMIZATION METHOD

Once the type of aircraft has been determined, the area of the wing, the unstick speed, the flight height, the travel distance (horizontal distance from take-off to cruise), the cruise velocity and the endurance of aircraft can be derived, with the thrust demand during the cruise and climb phase being constant. k_1, k_2 and k_3 can be derived by calculating, while the rotation speed during the cruise and climb phase are known, the optimization method of the propulsion system are as follows:

1) The optimum and efficient rotation speed of the propeller follows the set of equations below:

$$\begin{cases} n_{\text{s\_opt}} = n_{\text{s\_c}} + n\Delta n_s \\ n_{\text{s\_opt}} \le n_{\text{s\_f}} \end{cases} \tag{18}$$

where $n_{\text{s\_opt}}$ is the optimum and efficient rotation speed of the propeller; $n_{\text{s\_c}}$ is the propeller rotation speed of the minimum thrust demands during the climb cruise phase; $n_{\text{s\_f}}$ is the propeller rotation speed of the minimum thrust demands during the climb climb phase; Δn_s is the offset of the propeller rotation speed; $n = 0, 1, 2, 3 \ldots$.

2) $n = 0$, the aero foil, blade-number and diameter of the propeller can be derived, through the aerodynamic performance of aircraft, the preliminary design of the propeller is completed by the leaf design theory of the traditional high efficiency propeller [24], By choosing the appropriate pitch angle of propeller, $n_{\text{s\_opt}}$ is the optimum and efficient rotation speed of the propeller. η_{per} and η_{pcr} can be derived by calculation, η_{per} is the propeller efficiency during the cruise phase, η_{pcr} is the propeller efficiency during the climb phase.

3) The climb power of aircraft can be derived from equation 8, and the motor and controller can be derived through the climb power of aircraft, meanwhile, the propulsion system weight can be calculated, where m_{ES} is the propulsion system weight.

4) The energy consumed can be derived from equation 15, where $E^{(1)}$ is the energy consumed.

5) n=1, Repeat step (1)~(4), $E^{(2)}$, $E^{(3)} \ldots E^{(\text{n})}$ can be derived by calculating.

6) If $|n_{\text{s\_opt}} - n_{\text{s\_f}}| < \varepsilon$, the iteration end; otherwise, $n = n + 1$, repeat step (1)~(4).

7) $E^{(1)}$, $E^{(2)} \ldots E^{(\text{n})}$ can be derived by calculating, $E_{min} = |E^{(1)}, E^{(2)} \ldots E^{(\text{n})}|$.

8) The rotation speed of the propeller can be derived by calculating under the minimum energy consumed E_{min}.

IV. EXPERIMENT DESIGN AND SETUP

A. EXPERIMENT SETUP

For a given electric aircraft, three electric propulsion systems were designed under the requirements from for propellers with different peak efficiency operating points [25]. The peak efficiency operating point for propellers are the optimums operating point, the climb phase and the cruise phase respectively. By testing three systems and comparing their energy consumption, the proposed method can be verified [26].

The flight profile and design parameters are shown in Table 1 and Table 2

TABLE 1. Flight profile of the aircraft.

Phase	Time(min)	Rotational Speed (rpm)	Minimum Power Requirement(kW)
ground Roll	1	1400	8.5
takeoff	5	2300	24
cruise	20	1500	8.9
glide landing	4	500	0.5

TABLE 2. Design parameters of aircraft.

Phase	Minimum Power Requirement(kW)
wing area(m^2)	10
cruise speed(km /h)	150
unsticks speed(km /h)	58
flight height(m)	1000
climb angle	0.12
resistance coefficient	0.08

B. DESIGN OF THE PROPULSION SYSTEM

The efficiency of the designed propeller systems can be determined using equation 4. Table 3 shows the rotational speed under peak efficiency point and the takeoff efficiency of the propeller [27].

TABLE 3. Rotational speed under peak efficiency and efficiency during takeoff of fixed-pitch propellers.

Peak efficiency point	Takeoff	Cruise	Optimum efficiency point
rotational speed(rpm)	2300	1500	1650
takeoff efficiency(%)	70	55	60

According to equation 6, during the takeoff phase, the power consumption is 19kW, the efficiency of the motor and the controller are 93% and 95%. The power demand of the propulsion systems can be determined using equation 8, which are 27kW, 35kW and 32kW for propellers whose peak efficiency operating points are at the takeoff phase, the cruise phase and the optimum operating point respectively. Therefore, the motors used are permanent-magnet synchronous motors whose power is 30kW, 40kW and 35kW. Details of the motors are shown in Table 4.

The drag coefficient and the power coefficient are in proportion to the number of blades. Two-blade propellers are

TABLE 4. Performance parameter of the motors.

parameter	the highest efficiency point of propeller in		
	takeoff	cruise	optimum efficiency point
power(kW)	30	40	35
rated speed (rpm)	2300	2300	2300
maximum speed(rpm)	2500	2500	2500
rated torque(N·m)	143	160	150
rated efficiency(%)	93	93	93
maximum working voltage(V)	450	450	450
maximum working current(V)	150	170	160
weight(kg)	17	25	20

most commonly used in lightweight aircrafts for their simple construction [28]. The experiment aircraft also uses two-blade propeller. The diameter for the propeller during the cruise phase can be calculated as [29]:

$$D = k_d(\frac{P}{v\Delta\Omega^2})^{0.25} \tag{19}$$

where k_d is the diameter coefficient whose value is 106.5; P is the power demand of the propeller which is 10.4kW given by the 1500rpm minimum cruise rotational speed of the motor; Δ is the relative air density, is 1; v is the cruise speed, is 100km/h; D is the diameter of the propeller and can be determined to be 1.5m.

Given the 2300rpm rated rotational speed and 2500rpm maximum rotational speed, the rotational speed of the propeller is limited at 2200rpm. To further improve efficiency, the propeller is attached to the flange of the shaft to be directly driven by the motor. Figure 3 shows 3 propellers designed with peak efficiency at the takeoff phase (2300rpm), the cruise phase (1500rpm) and the optimum point(1650rpm) [30].

(a) The highest efficiency point in takeoff

(b) The highest efficiency point in cruise

(c) The highest efficiency point in optimum efficiency point

FIGURE 3. Three propellers.

The power ratings for the motors are 30kW, 40kW and 35kW. Given the fact that motors with power rating from 30kW to 50kW weight equally, we opt for a controller for 40kW motors for all 3 motors. The rated voltage for the controller is set to DC 450V considering the maximum input supply voltage of the aircraft is DC 400V [31].

V. EXPERIMENT RESULTS AND ANALYSIS

As shown in Figure 4, ground test is performed to test the proposed method. Figure 5 shows the measured thrust-rotational speed characteristic curve of propellers from 1300rpm to 2300rpm. The efficiency characteristic curve of the motor and the controller are shown in Figure 6 and Figure7, respectively.

FIGURE 4. Ground test aircraft.

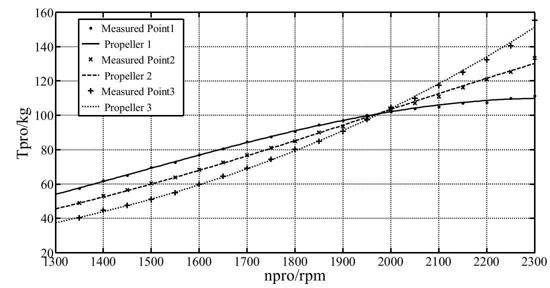


FIGURE 5. Characteristic curve of the propeller thrust.

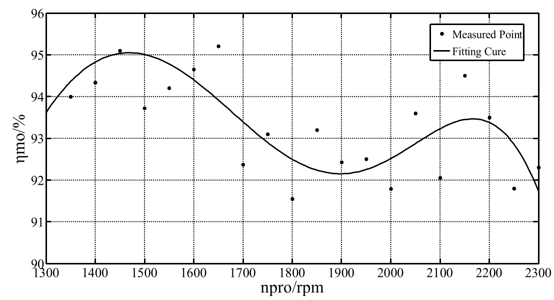


FIGURE 6. Characteristic curve of the motor efficiency.

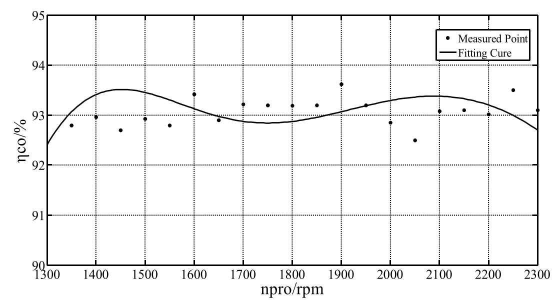


FIGURE 7. Characteristic curve of the controller efficiency.

Figure 8 and Figure 9 shows the efficiency characteristic curve from 1300rpm to 2300rpm of the propellers and the propulsion systems respectively. The efficiency of the propeller is measured in the Wind Tunnel Test environment with 72km/h wind speed. The efficiency of the propulsion systems are further calculated based on equation 2. Experimental results suggest that the takeoff efficiency of the motor and the controller are 92.8% and 91.8% respectively while the cruise efficiency of the motor and the controller are 92.8% and 94.6% respectively. The power demand of the propulsion system is 24kW during the takeoff phase and 8.9kW during the cruise phase.

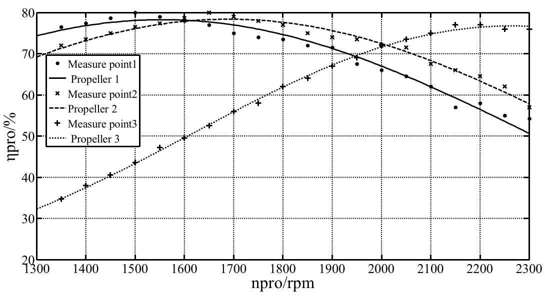


FIGURE 8. Characteristic curve of the propeller efficiency.

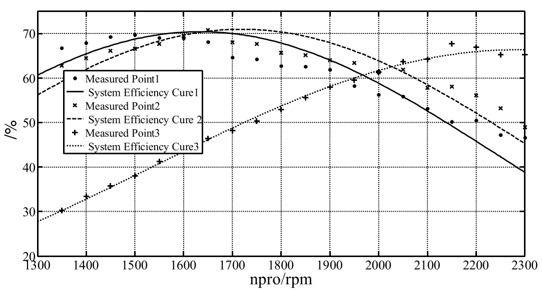


FIGURE 9. Characteristic curve of the propulsion system efficiency.

For the propeller designed to operate at peak efficiency during the cruise phase (the rotational speed is 1500rpm), the efficiency of the propeller is 68% during the takeoff phase and 80% during the cruise phase. The efficiency of the propulsion system is 57.9% during the takeoff phase and 70.2% during the cruise phase. The power of the propulsion system is 41.5kW during the takeoff phase and 12.7kW. Therefore, the energy consumed by the aircraft per flight (5 minutes takeoff and 20 minutes cruise) is 7.7kWh.

For the propeller designed to operate at peak efficiency during the cruise phase, the efficiency of the propeller is 80% during the takeoff phase and 65% during the cruise phase. The efficiency of the propulsion system is 68.2% during the takeoff phase and 56.4% during the cruise phase. The power of the propulsion system is 35.2kW during the takeoff phase and 15.8kW. Therefore, the energy consumed by the aircraft per flight is 8.2kWh.

In contrast, for the propeller with optimum peak efficiency operating point, the efficiency of the propeller is 76% during the takeoff phase and 75% during the cruise phase. The efficiency of the propulsion system is 64.7% during the takeoff phase and 65.8% during the cruise phase. The power of the propulsion system is 37.1kW during the takeoff phase and 13.5kW. Therefore, the energy consumed by the aircraft per flight is 6.1kWh.

As summarized above, for the propeller designed with optimum peak efficiency operating point based on the proposed method, energy consumption per flight is 1.6kWh less that when equipped with the propeller operates at peak efficiency during the cruise phase, and 2.1kWh less than the propeller operates at peak efficiency during the takeoff phase. As indicated from the experimental results, by properly optimizing the propeller with appropriate peak efficiency operating point, the efficiency of the propulsion system can be effectively improved, which decreases energy consumption of the aircraft.

VI. CONCLUSION

1) The energy consumption of electric aircrafts is determined by the efficiency of the propulsion system which is affected by the efficiency of the motor, the controller and the propeller. Unlike the motor and the controller which can maintain high efficiency in both takeoff and cruise phases, the propeller has much limited high efficiency operating range. Therefore, the energy consumption is mainly impacted by the peak efficiency operating point of the propeller.

2) The capacity of the motor and the controller is proportional to the power demand of the aircraft during takeoff, and inversely proportional to the efficiency of the motor, the controller and the propeller.

3) More than 98% of the energy consumed during takeoff and cruise. The proposed method can determine optimum peak efficiency operating point of the propeller with objective as minimizing energy consumption of the propulsion system.

This paper proposes an effective method to reduce the energy consumption of electric aircrafts by optimizing the peak efficiency operating point of the propeller. Experimental result from ground test indicates that the aircraft adopting the proposed method consumes 10% less energy.

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SHULI WANG was born in Tangshan, China, in 1980. He received the master's degree in electric machines and electric apparatus from the School of Electrical Engineering, Shenyang University of Technology, in 2009, where he is currently pursuing the Ph.D. degree. He is also an Electrical Engineer with the Liaoning General Aviation Academy. His research interest includes the modeling and optimal control of motor driving systems of electric aircraft.

SHUO ZHANG received the B.Eng. degree from the North China Institute of Aerospace Engineering, Hebei, China, in 2011, and the Ph.D. degree in vehicle engineering from the Beijing Institute of Technology, Beijing, China, in 2017.

He is currently an Assistant Professor with the National Engineering Laboratory for Electric Vehicles, School of Mechanical Engineering, Beijing Institute of Technology. His research interests include the modeling and control for the permanent magnet synchronous motor, multimotor driving systems, and hybrid power systems.

SHAOHUA MA received the bachelor's and Ph.D. degrees from the Shenyang University of Technology, in 1988 and 2008, respectively, all in electrical engineering. She has been the Head of Department of Electrical Machinery, since 2014. She is currently a Professor with the School of Electrical Engineering, Shenyang University of Technology. Her research interests include renewable energy generation, intelligent electrical apparatus, and advanced digital control technique and power electronics applications in power systems.