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RESEARCH ARTICLE

An Optimization Method for Improving Efficiency of Electric Propulsion System of Electric Seaplane

SHULI WANG[1,2,3], QINGXIN ZHANG[1], GUIWEN KANG[3], XINYUE FAN[3], SHUO ZHANG[4], (Member, IEEE), AND JIEQIU BAO[5]

[1]College of Artificial Intelligence, Shenyang Aerospace University, Shenyang 110136, China
[2]Key Laboratory of General Aviation, Shenyang Aerospace University, Shenyang 110136, China
[3]Liaoning General Aviation Academy, Shenyang 110136, China
[4]National Engineering Laboratory for Electric Vehicles, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[5]Engineering Training Center, Shenyang Institute of Engineering, Shenyang 110136, China

Corresponding author: Qingxin Zhang (zhangqx2002@163.com)

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ABSTRACT The takeoff process of a seaplane is different from that of a conventional land-based plane owing to the influence of hydrostatic, hydrodynamic, and aerodynamic forces. As a result, more energy will be consumed by the electric propulsion unit (EPU) of a seaplane during takeoff. Given the limited energy density of contemporary batteries, the energy consumed by the seaplane during its flight mission profile was minimized in this study by improving the efficiency of the EPU using a proposed optimization method. To meet the performance requirements of the seaplane EPU, the pitch angle of the propeller was taken as the optimization variable and the system loss was mathematically modeled. The performance of the EPU was thereby optimized, its consumption during flight was reduced, and the seaplane endurance was increased accordingly. The proposed optimization method was subsequently verified using a prototype test of a two-seat electric seaplane. The results show that the proposed method can reduce the energy consumption of the EPU by more than 5% during a single flight.

INDEX TERMS Electric seaplane, electric propulsion unit (EPU), energy efficiency optimization, prototype test.

NOMENCLATURE

ρ	Air density.
C_T	Propeller thrust coefficient.
β	Propeller power coefficient.
S	Wing area.
C_D	Aerodynamic drag coefficient.
C_L	Aerodynamic lift coefficient of the aircraft.
c_r	Water friction resistance coefficient.
ρ_w	Water density.
B	Float width.
N_P	Number of floats.
EPU	Electric propulsion unit.
θ	Pitch angle.

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I. INTRODUCTION

With the acceptance of the green development concept of ‘‘lucid waters and lush mountains as invaluable assets,’’ China has strengthened its comprehensive management and protection of lakes, river basins, and rivers. The electric seaplane is a pollution-free green energy fixed-wing aircraft that can take off, land, and park on the water surface. Similar to a conventional piston-powered aircraft, it can be used as a rescue or sightseeing aircraft on the water surface. The vigorous development of China's emergency rescue system and tourism industry in recent years has increased the potential value of electric seaplanes to China's aviation industry [1].

Seaplanes are different from conventional land-based planes in that during the process of taking off from and landing on the water surface, motion parameters such as the pitch angle and lift (ship's draft) change with speed owing to the combined influence of hydrostatic, hydrodynamic, aerodynamic, and gravity forces, which are determined by the interactions among the hydrodynamic and aerodynamic characteristics of the aircraft [2]. The seaplane takeoff process can be divided into four stages based on the associated hydrodynamic and aerodynamic characteristics: taxiing, transitional taxiing, high-speed taxiing, and takeoff. Each stage exhibits unique characteristics, and the transition between different stages can be determined according to the pitch angle of the aircraft. The changes in the pitch angle and hydrodynamic resistance in the four stages are shown in Figure 1 [3].

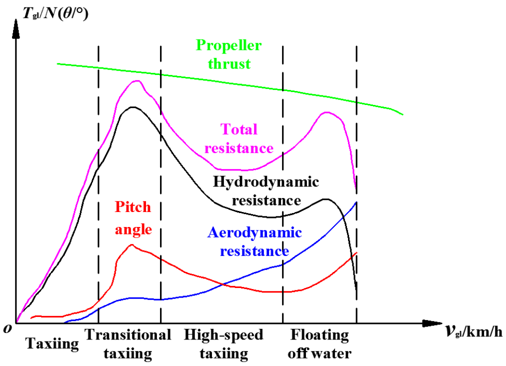

FIGURE 1. Variation of pitch angle and hydrodynamic resistance.

The speed is relatively low during the taxiing stage at approximately 25% of the seaplane's takeoff velocity. The motion in this state is similar to that of a ship sliding in water. The pitch angle increases continuously with increasing speed as the water resistance increases approximately linearly [4].

As the speed of the aircraft continues to increase during the transitional taxiing stage, a large quantity of water accumulates in front of the hull, the fore body breaks away from the water, the aircraft draught decreases, the trim angle and water resistance increase significantly, and the buoyancy point moves back continuously. Once the buoyancy point moves to the center of gravity of the aircraft, the pitch angle and water resistance reach peak values, forming an initial resistance peak, then both gradually decrease. The speed in this stage is between 25% and 50% of the takeoff velocity [5].

During the high-speed taxiing stage, the continuous increase in speed further lifts the hull, reduces the area of the waterline, and decreases the pitch angle and water resistance. The speed in this stage is approximately 50% to 80% of the takeoff velocity.

During the takeoff stage, the sliding speed gradually increases, the pitching angle increases, and the current scours along the bottom of the plane hull. Thus, the hydrodynamic resistance increases and the air resistance continue to increase, forming a second resistance peak. Subsequently, the hydrodynamic resistance decreases rapidly until it becomes zero as the seaplane leaves the water, and the takeoff phase ends. The speed in this phase is approximately 80% to 100% of the takeoff velocity [6].

The water landing of a seaplane follows the reverse of the takeoff process and can be divided into four stages accordingly: landing, high-speed taxiing, transitional taxiing, and taxiing. However, the landing speed of a seaplane is much lower than the takeoff speed and its landing distance is much shorter than its takeoff distance owing to the use of a spoiler during landing process. Thus, much less energy is consumed by an electric propulsion unit (EPU) during landing on water. To simplify the analysis of EPU efficiency, the energy consumed during the landing stages was ignored in this study, and only the energy consumed by the EPU during the takeoff, climbing, and cruising stages was considered. However, in practical applications, a certain amount of battery power should be reserved to ensure safe landing of the aircraft on the water surface [7].

To ensure the safety of an electric seaplane, the power of the EPU should not only satisfy the demands of takeoff and climbing, but also facilitate the endurance of the aircraft. As a result, the takeoff and cruise characteristics of seaplanes must be analyzed and the structure of their EPUs optimized accordingly to reduce losses [8].

Scholars around the world have published little research on the optimization of the EPU for electric seaplanes; most research has focused on optimizing the efficiency of the EPU for land-based electric aircraft [9]. Several scholars have selected motors and motor controllers by combining the design parameters of land-based electric aircraft and taking the maximum power demand (during the takeoff stage) from the aircraft operating profile as the design input [10]. The parameter matching method has been employed to optimize the structure of an aircraft EPU and thereby improve its efficiency; an experimental verification of this optimization was subsequently performed [11]. The disadvantage of this method is that it does not consider the effects of the aircraft operating profile, electromechanical characteristics of the motor and motor controller, or aerodynamic characteristics of the propeller on the efficiency of the EPU. Under these operating conditions, the objective of optimization is to minimize the total energy consumption of the aircraft when completing a flight mission profile [12]. A decoupling method employing a mathematical model coupling the electromechanical characteristics of the motor and motor controller with the aerodynamic characteristics of the propeller was therefore proposed and the structure of the EPU optimized accordingly.

Owing to the influence of various aerodynamic and hydrodynamic resistances, the energy consumption of the EPU in a seaplane during takeoff is higher than that of the EPU in a land-based aircraft, accounting for approximately 10% of the energy consumption of the entire flight profile [13]. Thus, an EPU energy efficiency optimization method developed for a land-based electric aircraft is not suitable for a seaplane [14]. However, an energy efficiency optimization model for the EPU of the seaplane can be constructed by analyzing the takeoff process on the water. Indeed, the aerodynamic characteristics of the propeller and the electromechanical characteristics of the motor and motor controller can be combined to optimize the energy efficiency of a seaplane EPU and improve its performance [15]. Given that the use of

EPUs in aircraft is presently constrained by the low energy density of batteries, the focus of this study was to increase the range of an electric seaplane by optimizing the energy efficiency of its EPU [16].

Electric seaplanes are different from conventional land-based electric aircraft in that the taxiing and takeoff stages of the former are more complicated than those of the latter, and thus, the energy consumption of the EPU in the former is much higher than that of the EPU in the latter; this difference is often neglected.

In this study, the EPU of an electric seaplane was analyzed during the water takeoff, climbing, and cruising processes to propose an optimization design method improving its efficiency. By analyzing the hydrodynamic characteristics during the electric seaplane taxiing and takeoff stages and considering the flight mission profile of the aircraft, an energy consumption calculation model was established for the aircraft according to flight stage, and a method for efficiency optimization of the EPU was established.

The proposed optimization method changes the pitch angle of the propeller to optimize the efficiency of the aircraft EPU and reduce its energy consumption, enabling it to complete the designated flight mission profile. This EPU efficiency optimization method was shown to effectively reduce the energy consumption of the aircraft EPU while meeting the power performance requirements of the aircraft.

II. EPU COMPOSITION AND ENERGY CONSUMPTION ANALYSIS

A. EPU COMPOSITION

Figure 2 shows a block diagram of the EPU of a selected electric seaplane; the EPU is primarily composed of a propeller, electric motor, motor controller, battery, human–computer interactive control and display system, throttle lever, and auxiliary power supply [17]. The motor controller converts the electric current of the battery into a three-phase alternating current that supplies power to the motor; the motor drives the propeller to generate the thrust required by the seaplane [18]. The pilot controls the throttle lever in the cockpit to adjust the propeller speed, thereby controlling the running state of the aircraft. The human–computer interactive control and display system provides data describing real-time working state of the motor, controller, and battery. This system and the control module are powered by an auxiliary power supply.

The battery in the selected seaplane is located in the compartment behind the aircraft cabin. After the flight mission, when the battery energy is insufficient, the battery is removed and placed on a charging station near the hangar. When the total charging time reaches the limit or the battery capacity drops to 80% of its rated capacity, the batteries are replaced [19]. Because the energy in the battery is primarily consumed during the takeoff, climbing, and cruising stages, this study focused on the efficiency and energy consumption during these three stages.

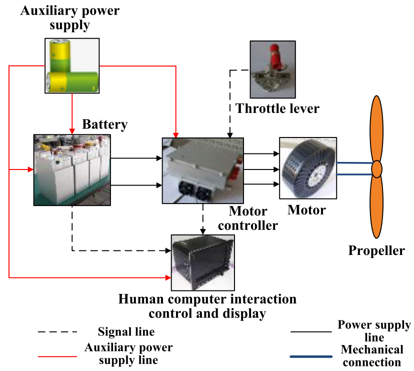

FIGURE 2. Block diagram of an EPU.

B. PROPELLER DESIGN AND PERFORMANCE ANALYSIS

A fixed-pitch propeller is typically used to provide thrust for electric seaplanes. As its performance directly affects the aircraft performance, the design of the fixed-pitch propeller is a critical consideration. In this study, the high-efficiency propeller optimization method proposed in was applied to vary the pitch of a typical fixed-pitch propeller according to design parameters including flight speed, propeller thrust demand, propeller airfoil, number of propeller blades, and efficient working point [20]. The typical fixed-pitch propeller of a two-seat electric seaplane is shown in Figure 3.

FIGURE 3. Propeller of a two-seat electric seaplane.

According to the aerodynamic theory of propeller operation, the thrust output of a propeller can be approximately expressed as a function of the propeller speed as follows [21]:

$$\begin{cases} T_{\mathrm{p}} = 16 C_{\mathrm{T}} \rho R_{\mathrm{p}}^{4} n_{\mathrm{p}}^{2} \\ W_{\mathrm{p}} = 32 \beta \rho R_{\mathrm{p}}^{5} n_{\mathrm{p}}^{3} \end{cases} \tag{1}$$

where T_{P} is the propeller output thrust; W_{p} is the propeller power requirement; R_{p} is the propeller radius; C_{T} characterizes the influence of factors such as the pitch angle, airfoil, and number of blades on the propeller thrust; β takes a value according to the propeller pitch angle, airfoil shape, and number of blades; since the selected electric seaplane only flies at a low altitude (below 500 m), ρ was approximated as 1.29 kg/m^3; and n_{p} is the propeller speed. Note that the variation of C_{T} and β with the propeller rotation speed can be determined for a fixed pitch angle using the results of propeller wind tunnel tests.

When finalizing the propeller airfoil configuration and number of blades, the efficient working speed of the propeller can be adjusted by changing the pitch angle to fine tune its efficiency. If the pitch angle is too small, the angle of attack is also too small, as are the thrust and effective power generated by the propeller, and the efficiency is extremely low [22]; in contrast, if the pitch angle is too large, the resistance generated by the rotation of the propeller is high and the efficiency of the propeller is extremely low. The efficiency curve of the propeller for a two-seat electric seaplane at different pitch angles, obtained through simulation, is shown in Figure 4 according to the incoming flow speed and can be calculated as [23]:

$$\eta_{\mathrm{p}} = \frac{C_{\mathrm{T}} v_{\mathrm{p}}}{2 n_{\mathrm{p}} R_{\mathrm{p}} \beta} \tag{2}$$

where η_{p} is the efficiency of the propeller and v_{p} is the propeller flow velocity.

Equation (2) demonstrates that the propeller efficiency is affected by the incoming flow speed. Numerical calculations can therefore be conducted to obtain the efficiency curve of the propeller at a fixed pitch angle according to incoming flow speeds as shown in Figure 5.

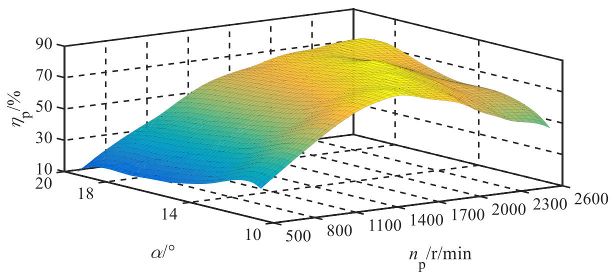

FIGURE 4. Propeller efficiency according to pitch angle.

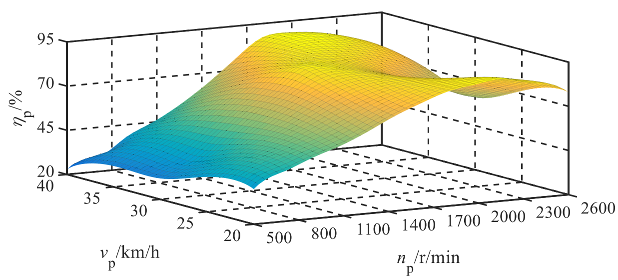

FIGURE 5. Propeller efficiency according to incoming flow speed.

Thus, the EPU efficiency can be improved and the energy consumption required to complete a flight mission profile reduced by optimizing the pitch angle of the propeller to minimize losses. To do so, the hydrodynamic characteristics of the electric seaplane must first be analyzed to obtain the losses incurred during the flight.

C. ANALYSIS OF SEAPLANE HYDRODYNAMIC CHARACTERISTICS

During the takeoff stage, an electric seaplane is affected by its weight, propeller thrust, aerodynamic lift, aerodynamic drag, hydrodynamic lift, and hydrodynamic resistance [24]. Assuming that the electric seaplane glides horizontally in the water, the forces in the vertical direction are balanced, and the acceleration is approximately zero. Furthermore, the propeller speed is assumed to be capable of real-time adjustment to manage the propeller output thrust, ensuring that the horizontal acceleration remains unchanged during the entire taxiing and takeoff process on the water surface. The forces in this condition are shown in Figure 6 and the related motion equation is expressed as follows:

$$\begin{cases} m a_{\mathrm{gl}} = T_{\mathrm{gl}} \cos(\theta + \varphi) - T_{\mathrm{D}} - T_{\mathrm{W}} \\ T_{\mathrm{AL}} = mg - T_{\mathrm{gl}} \sin(\theta + \varphi) - T_{\mathrm{L}} \\ v_{\mathrm{gl}} = v_0 + a_{\mathrm{gl}} t \\ v_{\mathrm{fl}} = \dfrac{v_{\mathrm{gl}}}{\cos(\theta + \varphi)} \end{cases} \tag{3}$$

where a_{gl} is the horizontal acceleration during the takeoff process; θ is the pitch angle; φ is the angle between the pull line of the EPU and the lower structural line of the aircraft, which can be determined once the aircraft design is finalized; m is the takeoff weight; t is the time required for the aircraft to take off from the water; v_{gl} is the taxiing speed in the horizontal direction of the aircraft; v_{fl} is the flight speed of the aircraft in the axial direction, which is approximately equal to the forward speed of the propeller; T_{gl} is the thrust of the propeller during the taxiing and takeoff stage; v_0 is the water taxiing speed of the aircraft; $T_{\mathrm{D}}$is the aerodynamic resistance; T_{W} is the hydrodynamic resistance; T_{L} is the aerodynamic lift; and T_{AL} is the hydrodynamic lift.

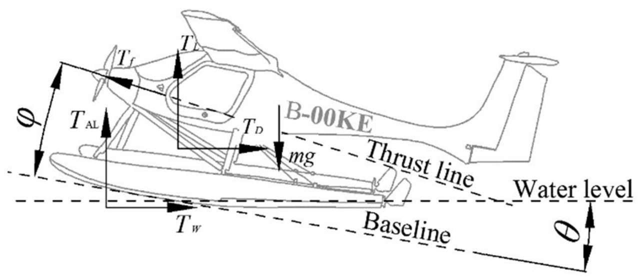

FIGURE 6. Force analysis of a seaplane during takeoff.

The aerodynamic drag T_{D} on the seaplane can be approximated as [25]:

$$T_{\mathrm{D}} = \frac{\rho S C_{\mathrm{D}}}{2} v_{\mathrm{gl}}^2 \tag{4}$$

The aerodynamic lift T_{L}on the seaplane can be approximately expressed as [26]:

$$T_{\mathrm{L}} = \frac{\rho S C_{\mathrm{L}}}{2} v_{\mathrm{gl}}^2 \tag{5}$$

The hydrodynamic resistance T_{W} can be expressed as a function of the seaplane taxiing speed and propeller thrust [27]:

$$T_{\mathrm{W}} = T_{\mathrm{AL}} \tan\theta + c_{\mathrm{r}} \frac{\rho_{\mathrm{w}} v_{\mathrm{gl}}^2}{2} S_{\mathrm{w}} \tag{6}$$

where c_{r} can be approximately taken as 0.074; and S_{W} is the landing area of the seaplane, which can be expressed as [28]:

$$S_{\mathrm{w}} = \frac{T_{\mathrm{AL}} N_{\mathrm{p}}^2 B^2}{0.35\pi \rho_{\mathrm{w}} v_{\mathrm{gl}}^2 \theta N_{\mathrm{p}} B - 1.4 T_{\mathrm{AL}}} \tag{7}$$

During the process of seaplane takeoff, θ can be expressed as a function of taxiing speed. Its characteristic function is related to the aircraft type and water characteristics, and the function curves can be obtained by the least-squares polynomial parameter identification method based on the aircraft flight test data as follows [29]:

$$\theta = f_1(v_{\mathrm{gl}}) \tag{8}$$

According to the operating conditions, the flight of an electric seaplane can be divided into five flight stages: taxiing and takeoff, climbing, cruising, descending, and landing. The energy consumption will be different in each flight stage. Thus, each flight stage must be analyzed to optimize the structure of the seaplane EPU and improve its comprehensive efficiency. As the systematic energy consumption of the seaplane EPU will be lower during the descending and landing stages, the energy consumption during these stages was ignored to facilitate analysis.

D. ENERGY CONSUMPTION ANALYSIS OF FLIGHT PROFILE

1) TAKEOFF STAGE

The takeoff stage of the aircraft comprises taxiing, transition taxiing, high-speed taxiing, and takeoff from water. The speed of the aircraft entering the taxiing phase is given by v_{st}; when the speed of the aircraft reaches v_{fw}, the aircraft takes off from the water and enters the climbing stage. Therefore, based on equations (1) to (8), the energy demand of the EPU during the takeoff stage can be expressed as [30]:

$$\begin{cases} E_{\mathrm{gl}} = \dfrac{\int_0^{t_{\mathrm{gl}}} 32\beta\rho n_{\mathrm{gl}}^3 R_{\mathrm{p}}^5 \mathrm{d}t}{\eta_{\mathrm{m\_gl}}\eta_{\mathrm{c\_gl}}} \\ 16C_{\mathrm{T}}\rho R_{\mathrm{p}}^4 v_{\mathrm{gl}}^2 = m(a_{\mathrm{gl}}\cos\theta + g\sin\theta) + \dfrac{1}{2}v_{\mathrm{gl}}^2(\rho S C_{\mathrm{D}}\cos\theta \\ \qquad -\rho S C_{\mathrm{L}}\sin\theta + c_{\mathrm{r}}\rho_{\mathrm{w}} S_{\mathrm{w}}\cos\theta) \\ a_{\mathrm{gl}} = \dfrac{v_{\mathrm{fw}} - v_{\mathrm{st}}}{t_{\mathrm{gl}}} \\ v_{\mathrm{gl}} = v_{\mathrm{st}} + a_{\mathrm{gl}} t \\ \theta = f_1(v_{\mathrm{gl}}) \end{cases} \tag{9}$$

where E_{gl} is the energy required by the aircraft, $\eta_{\mathrm{m\_gl}}$ is the motor efficiency, $\eta_{\mathrm{c\_gl}}$ is the efficiency of the controller, n_{gl} is the rotational speed of the propeller, and t_{gl} is the time required for the entire taxiing and takeoff process.

2) CLIMBING STAGE

Once the seaplane takes off, its float leaves the water and it enters the climbing stage. The climbing of the seaplane is the same as that of a land-based plane. During the climbing stage, the propeller continues to run at maximum speed and the output thrust remains unchanged. Assuming that the climbing height and angle of the aircraft are fixed and referring to the calculation of EPU energy demand for a land-based plane, the energy demand of the seaplane EPU during the climbing stage can be approximated as [31]:

$$\begin{cases} E_{\mathrm{cl}} = \displaystyle\int_0^{\frac{2H\cot\gamma}{v_{\mathrm{cr}}+v_{\mathrm{fw}}}} \dfrac{16C_{\mathrm{T}}\rho R_{\mathrm{p}}^4 n_{\mathrm{cl}}^2 v_{\mathrm{cl}}\cos\gamma}{\eta_{\mathrm{m\_cl}}\eta_{\mathrm{c\_cl}}\eta_{\mathrm{p\_cl}}}\mathrm{d}t \\ v_{\mathrm{cl}} = v_{\mathrm{fw}} + \dfrac{(v_{\mathrm{cr}}^2 - v_{\mathrm{fw}}^2)\tan\gamma}{2H}t \\ \eta_{\mathrm{p\_cl}} = \dfrac{C_{\mathrm{T}} v_{\mathrm{cl}}}{2n_{\mathrm{cl}}R_{\mathrm{p}}\beta} \end{cases} \tag{10}$$

where E_{cl} is the energy demand of the seaplane, v_{cr} is the cruising speed of the aircraft, v_{cl} is the cruising speed of the seaplane, γ is the climbing angle, H is the cruising altitude of the seaplane, n_{cl} is the rotational speed of the propeller, $\eta_{\mathrm{m\_cl}}$ is the motor efficiency, $\eta_{\mathrm{c\_cl}}$ is the controller efficiency, and $\eta_{\mathrm{p\_cl}}$ is the propeller efficiency.

3) CRUISING STAGE

Once the seaplane climbs to its cruising altitude H, it enters the cruising stage, which is the same as that of a land-based plane. During the cruising stage, the propeller thrust is adjusted to maintain the aircraft as it flies at a constant speed. The energy demand of the EPU of the aircraft in the cruising stage can therefore be expressed as [32]:

$$E_{\mathrm{cr}} = \frac{32\beta C_{\mathrm{T}}\rho R_{\mathrm{p}}^5 n_{\mathrm{cr}}^3 t_{\mathrm{cr}}}{C_{\mathrm{T}}\eta_{\mathrm{m\_cr}}\eta_{\mathrm{c\_cr}}} \tag{11}$$

where t_{cr} is the cruising time of the aircraft; n_{cr} is the rotational speed of the propeller, which is approximately constant during the cruising stage; $\eta_{\mathrm{m\_cr}}$ is the motor efficiency; $\eta_{\mathrm{c\_cr}}$ is the controller efficiency; and $\eta_{\mathrm{p\_cr}}$ is the propeller efficiency.

Based on equations (9) ~ (11), the energy consumed by the EPU of an seaplane while completing a flight mission can be expressed as:

$$\begin{cases} E_{\mathrm{es}} = E_{\mathrm{gl}} + E_{\mathrm{cl}} + E_{\mathrm{cr}} \\ E_{\mathrm{gl}} = \dfrac{\int_0^{t_{\mathrm{gl}}} 32\beta\rho n_{\mathrm{gl}}^3 R_{\mathrm{p}}^5 \mathrm{d}t}{\eta_{\mathrm{m\_gl}}\eta_{\mathrm{c\_gl}}} \\ E_{\mathrm{cl}} = \displaystyle\int_0^{\frac{2H\cot\gamma}{v_{\mathrm{cr}}+v_{\mathrm{fw}}}} \dfrac{16C_{\mathrm{T}}\rho R_{\mathrm{p}}^4 n_{\mathrm{cl}}^2 v_{\mathrm{cl}}\cos\gamma}{\eta_{\mathrm{m\_cl}}\eta_{\mathrm{c\_cl}}\eta_{\mathrm{p\_cl}}}\mathrm{d}t \\ E_{\mathrm{cr}} = \dfrac{32\beta C_{\mathrm{T}}\rho R_{\mathrm{p}}^5 n_{\mathrm{cr}}^3 t_{\mathrm{cr}}}{C_{\mathrm{T}}\eta_{\mathrm{m\_cr}}\eta_{\mathrm{c\_cr}}} \\ v_{\mathrm{cl}} = v_{\mathrm{fw}} + \dfrac{(v_{\mathrm{cr}}^2 - v_{\mathrm{fw}}^2)\tan\gamma}{2H}t \\ \eta_{\mathrm{p\_cl}} = \dfrac{C_{\mathrm{T}} v_{\mathrm{cl}}}{2n_{\mathrm{cl}}R_{\mathrm{p}}\beta} \\ \theta = f_1(v_{\mathrm{gl}}) \end{cases} \tag{12}$$

Equation (12) indicates that, once the overall design of the seaplane is completed, because the acceleration of the seaplane remains constant during the takeoff stage, the cruise speed, climbing angle, flight altitude, wing area, cruising time, aerodynamic drag coefficient, and lift drag ratio coefficient can be considered approximately constant. The energy consumed by the EPU when completing a flight mission is therefore solely dependent on the pitch angle of the aircraft during the takeoff phase, motor efficiency, motor controller efficiency, cruise speed, propeller pitch angle, and propeller rotation speed. During the process of completing a flight mission profile, the motor and motor controller can always work under highly efficient conditions; this efficiency can be regarded as approximately constant. Given the same water area and consistent meteorological conditions, the pitch angle variation of the aircraft in different stages of takeoff will be approximately the same; therefore, the energy consumption of the EPU while completing a flight mission profile is only related to the rotational speed and pitch angle of the propeller [33].

III. ESTABLISHMENT OF SYSTEM OPTIMIZATION METHOD

In the process of completing a flight mission, the thrust provided by the seaplane propeller is highest during the climbing stage. The maximum thrust output can be achieved by adjusting the pitch angle of the propeller. To ensure safe and reliable flight, the maximum thrust output of the propeller should satisfy the minimum thrust requirement during the climbing stage. A system optimization method to minimize EPU energy consumption was therefore developed assuming a consistent takeoff speed v_{fw} and cruising time for a given flight mission profile [34]. The proposed EPU optimization method is based on the known characteristic curve of the seaplane pitch angle change during takeoff. First, according to the design requirements of the seaplane and the maximum propeller efficiency when the aircraft is cruising, a propeller was designed with an adjustable pitch angle, as shown in Figure 3. Next, given the initial pitch angle and step length of the propeller, the energy consumption of the EPU was calculated as the aircraft completed a flight mission profile under different propeller pitch angles to obtain the minimum energy consumption. The corresponding optimal pitch angle of the propeller was subsequently identified to complete the EPU system optimization [35]. To verify the accuracy of the optimization results, they were compared with the highest propeller efficiency achieved during the takeoff stage and during the cruise stage.

According to Equation (12), the optimal objective function of the EPU can be expressed as follows:

$$\begin{aligned} E_{\min} &= \min\left(E_{gl} + E_{cl} + E_{cr}\right) \\ &\text{sb.} T_{cl} \geq T_{cl\_\min} \\ &\theta = f_1(v_{gl}) \end{aligned} \tag{13}$$

where T_{cl_min} is the minimum thrust requirement of the propeller during the seaplane climbing phase.

Once the overall design of the aircraft is completed, the design parameters k_1, k_2, and k_3 are constant, the change process of the seaplane pitch angle in each taxiing and takeoff stage is similar, and parameters such as hydrodynamic resistance, aerodynamic resistance, aerodynamic lift, hydrodynamic lift, and landing area can be confidently calculated. The energy consumed by the EPU during the taxiing and takeoff stage can then be determined using the Newton–Leibniz equation and the energy consumption E_{gl} of EPU can be obtained according to the propeller pitch angle as the efficiencies of the motor and motor controller remain approximately constant. Thus, by adjusting the propeller pitch angle, the high-efficiency speed point of the propeller can be changed and the energy consumed by the EPU during the flight mission profile can be minimized. This optimal design method for the EPU of an electric seaplane can be expressed as follows [36]:

1: α_{min}, α_{max} $\leftarrow$ initialize maximum and minimum value of pitch angle;
2: $\Delta\alpha \leftarrow \alpha_{min}/10$;
3: $E_{es}[1..n]$, $\alpha[1..n]$;
4: $E_{min} = E_{es}$ [1];
5: for I $\leftarrow$ 1 to n do
6: if $\alpha\ [i] < \alpha_{max}$
7: if $E_{es}[i] < E_{min}$
8: $E_{min} \leftarrow E_{es}[i]$;
9: $\alpha_i \leftarrow \alpha_i + \Delta\alpha$;
10: return

where E_{min} is the minimum energy consumed by the seaplane when completing a flight mission and α_{min} is the propeller pitch angle corresponding to the minimum EPU energy consumption.

IV. PROTOTYPE TEST AND OPTIMIZATION VERIFICATION

A test was conducted to evaluate the seaplane EPU and thereby confirm the feasibility and accuracy of the proposed optimization method. First, a prototype aircraft and EPU were selected and their design parameters were obtained. The efficiency optimization of the aircraft EPU employed the design parameters of the aircraft and EPU to numerically calculate the propeller pitch angles corresponding to the minimum energy consumptions and highest efficiencies during the taxiing and takeoff, climbing, and cruising stages of the flight mission. A flight test of the prototype was subsequently undertaken using a consistent water area using the calculated propeller pitch angles. The test data was compared with the numerical results to verify the accuracy of the proposed optimization method [37].

A. PROTOTYPE SELECTION

A two-seat light sports seaplane was used as the test prototype, as shown in Figure 7. This electric seaplane uses a double-pontoon, single-wing structure. The specifications of the selected electric seaplane are provided in Table 1.

The performance of the seaplane's EPU should meet the power performance requirements of the aircraft; the EPU performance parameters are listed in Table 2.

The test data describing taxiing and takeoff in a certain water area indicated the seaplane pitch angles shown in Figure 8. The test data points in the figure were fitted to a curve using the nonlinear fitting method.

TABLE 1. Seaplane specifications.

Parameter	Value
Wing area S (m^2)	14.5
Aerodynamic drag coefficient C_D	6
Aerodynamic lift coefficient C_L	2.5
Float width B (m)	0.5
Number of floats N_p	2
Maximum takeoff weight m (kg)	600
Aircraft sailing speed v_{0l} (km/h)	20
Cruising speed v_c (km/h)	120
Aircraft speed from water v_{fw} (km/h)	100
Flight altitude H (km)	0.5
angle of climb γ	0.12
Water frictional resistance coefficient c_r	0.2
The angle between the thrust line and the lower configuration line of the aircraft θ	0.01
Aircraft cruise time (min)	40

TABLE 2. EPU specifications.

Parameter	Value
Minimum thrust requirement during the climb phase of the aircraft T_{cl_min} (N)	1244
Propeller radius R_p (m)	0.8
Motor efficiency η_m （%）	96
Controller efficiency η_c （%）	96
airfoil	RAF6
Adjustable range of propeller pitch angle （°）	10～20

FIGURE 7. Prototype two-seat light sport electric seaplane.

B. NUMERICAL CALCULATIONS

According to the seaplane design parameters listed in Table 1 and the EPU performance parameters provided in Table 2, the proposed optimization method was applied to determine the EPU efficiency. The efficiency was determined at four different pitch angles of 11°, 16°, 18°, and 20° with the following results:

(1) When the propeller pitch angle was 11°, the propeller exhibited the highest efficiency during the cruising stage; when the propeller pitch angle was 20°, the propeller exhibited the highest efficiency during the takeoff stage; when the propeller pitch angle was 16°, the aircraft exhibited the minimum energy consumed when completing the flight mission profile; and when the propeller pitch angle was 18°, the aircraft exhibited the highest efficiency during the takeoff stage.

(2) The times required for the takeoff and climbing stages were calculated to be 3 min and 1.5 min, respectively.

(3) The power demand and rotational speed characteristics of the propeller at different pitch angles, as obtained by the numerical calculations, are shown in Figures 9 and 10, respectively. Figures 11 and 12 show the propeller speed characteristics of the aircraft at different pitch angles during the climbing and cruising stages, respectively.

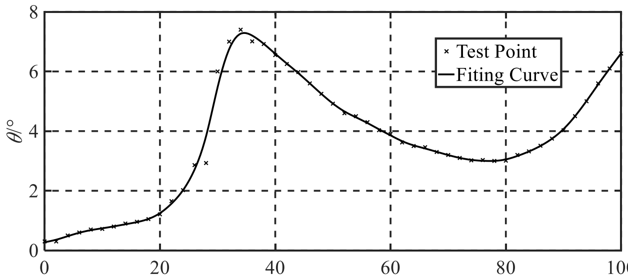

FIGURE 8. Characteristic curve of the seaplane pitch angle in a certain water area.

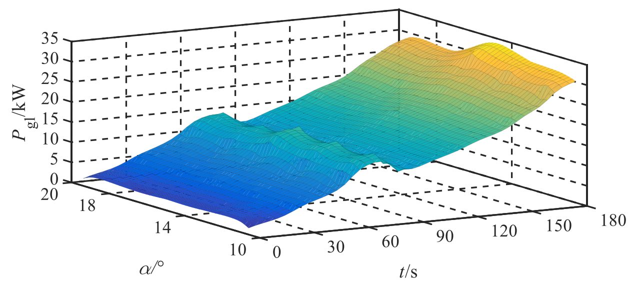

FIGURE 9. Propeller power characteristics at different pitch angles during the takeoff stage.

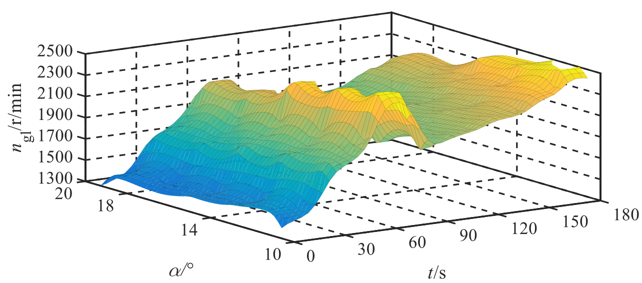

FIGURE 10. Propeller speed at different pitch angles during the takeoff stage.

C. PROTOTYPE TEST

The characteristics of the propeller speed and the input power characteristics of the EPU were measured during the prototype test at the same four pitch angles (11°, 16°, 18°, and 20) considered in the numerical calculations. Figures 13 to 15 depict the characteristic speed change

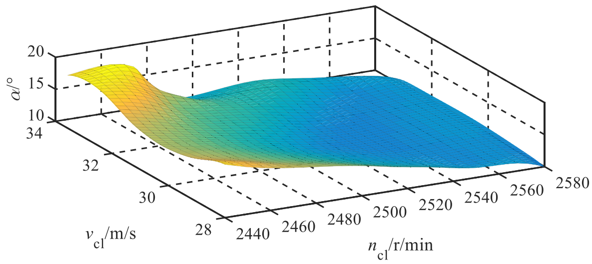

FIGURE 11. Propeller speed at different pitch angles during the climbing stage.

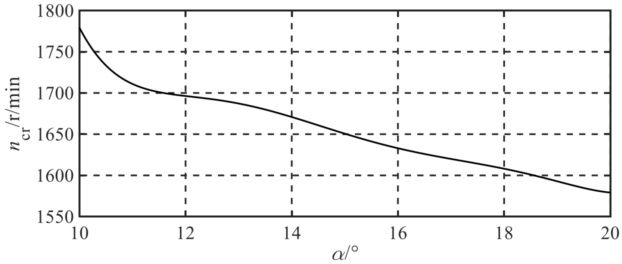

FIGURE 12. Propeller speed at different pitch angles during the cruising stage.

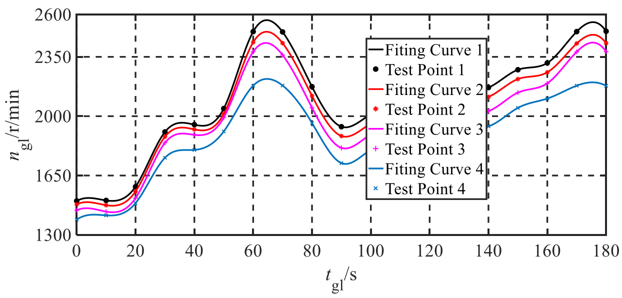

FIGURE 13. Propeller speed changes during the takeoff stage.

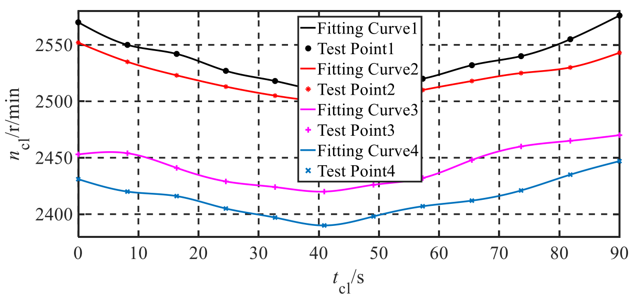

FIGURE 14. Propeller speed changes during the climbing stage.

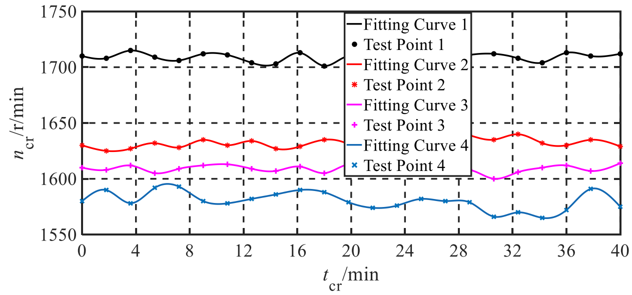

FIGURE 15. Propeller speed changes during the cruising stage.

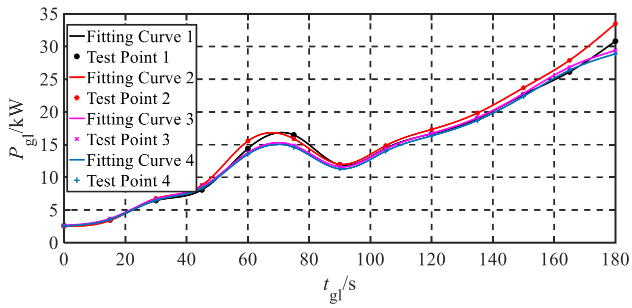

FIGURE 16. Input power characteristics of the EPU during the takeoff stage.

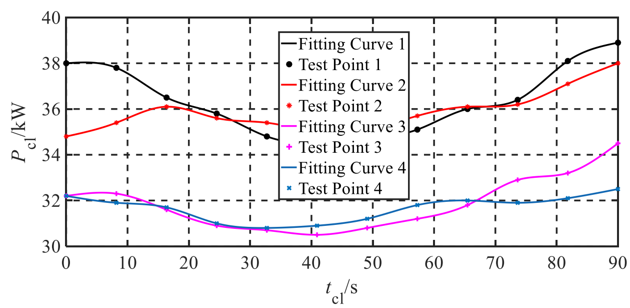

FIGURE 17. Input power characteristics of the EPU during the climbing stage.

of the propeller and Figures 15 to 17 illustrate the EPU input power change characteristics during the taxiing and takeoff, climbing, and cruising stages under these four pitch angles.

Figures 16 to 18 show that when the propeller pitch angle was designed to be the highest during the climbing (20°) and cruising (11°) stages, the seaplane EPU consumed 23.6 kWh and 22.7 kWh, respectively, while completing a single flight mission. When the pitch angle of the propeller was designed such that the EPU consumed the least energy during the takeoff stage (18°), the seaplane EPU consumed 23.1 kWh while completing one flight mission, and when the pitch angle of the propeller was designed to realize the smallest energy consumption throughout the entire flight mission (16°), the energy consumed by the seaplane EPU was 20 kWh. Compared with EPU energy consumptions of 23.6 kWh and 22.7 kWh when the propeller was optimized for the climbing and cruising stages, the optimal EPU design saved 3.6 kWh and 2.7 kWh, respectively. The EPU consumed the least energy during the takeoff stage, saving 3.1 kWh of electric energy. In summary, the proposed EPU efficiency optimization method was shown to reduce the energy consumed by the aircraft when completing a given flight mission by at least 13.5%. Therefore, adjusting the high-efficiency speed of the propeller by changing its pitch angle can effectively improve the overall efficiency of the aircraft EPU, reduce its energy consumption, and improve the aircraft endurance.

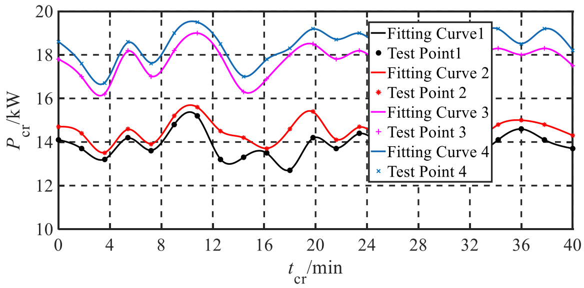

FIGURE 18. Input power characteristics of the EPU during the cruising stage.

When the flight mission profile of the aircraft changes, the proposed design method can be used to optimize the efficiency of the EPU by changing the pitch angle of the propeller, thereby effectively reducing the energy consumed by the EPU. Indeed, the use of a variable-pitch propeller can allow for adjustment according to the aircraft flight mission profile to optimize the EPU and reduce the energy consumed during the completion of any given flight mission.

V. CONCLUSION

(1) The efficiency of a seaplane EPU with a fixed-pitch propeller is related to the efficiencies of the motor, motor controller, and propeller. The range of the high-efficiency motor and motor controller is relatively high and flat, while the high-efficiency range of a fixed-pitch propeller is narrow, making it difficult to ensure that efficiency can be maintained during aircraft takeoff, climbing, and cruising. Therefore, the comprehensive efficiency of the EPU can be improved by adjusting the high-efficiency working point of the propeller, which can be accomplished by changing its pitch angle.

(2) An EPU optimization method was derived using propeller blade element theory to calculate the optimal pitch angle of the propeller in different flight stages. The performance at each of these angles was subsequently verified using the results of a prototype test.

(3) In the process of completing a flight mission, the energy consumed by the aircraft during takeoff, climbing, and cruising accounted for more than 95% of the total energy consumption. Given constant characteristics of a certain water area and considering the EPU energy consumption in these three stages, the maximum efficiency point of the propeller was adjusted to minimize the energy consumption of the aircraft EPU, effectively improving the flight endurance of the electric seaplane.

(4) Along with the continuous improvement in battery energy density, the proposed EPU efficiency optimization method can increase the comprehensive efficiency of electric seaplanes, lengthening their endurance and broadening their potential range of applications.

(5) In the future, research on different models of electric seaplane will be carried out, and EPU efficiency optimization method will be used to improve the comprehensive efficiency of EPU of electric seaplane of different types to increase their endurance.

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SHULI WANG was born in Tangshan, China, in 1981. He received the Ph.D. degree in electric machines and electric apparatus from the School of Electrical Engineering, Shenyang University of Technology, in 2020. He is currently an Electrical Engineer with the Key Laboratory of General Aviation, Shenyang Aerospace University. His research interest includes the modeling and optimal control of motor driving systems of electric aircraft.

QINGXIN ZHANG was born in 1970. He received the Ph.D. degree in electrical theory and new technology from the Shenyang University of Technology, Shenyang, China, in 2006.

He is currently a Professor with the School of Artificial Intelligence, Shenyang Aerospace University, and the Deputy Director of the Automatic Control Committee, Liaoning Institute of Aeronautics and Astronautics. His research interest includes the control science and engineering technology of aerospace propulsion systems.

GUIWEN KANG was born in Yixian, China, in 1972. He received the Ph.D. degree in mechanical manufacturing and automation from the Harbin Institute of Technology, in 2005.

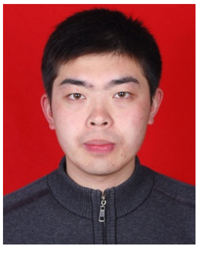
He is currently a Researcher with the Key Laboratory of General Aviation, Shenyang Aerospace University. His research interest includes the electronic propulsion units of electric aircraft.

XINYUE FAN was born in 1982. She received the B.Eng. degree from the College of Automation, Northwest University of Technology, in 2007.

She is currently the Deputy Chief of the Design Department with the Liaoning General Aviation Academy. Her research interest includes the design and development of electric propulsion systems for new energy aircraft.

SHUO ZHANG (Member, IEEE) 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 and the School of Mechanical Engineering, Beijing Institute of Technology. His research interests include the modeling and control for the permanent magnet synchronous motor, multi-motor driving systems, and hybrid power systems.



JIEQIU BAO was born in Shenyang, China, in 1983. He received the Ph.D. degree in electric machines and electric apparatus from the School of Electrical Engineering, Shenyang University of Technology, in 2016. He is currently an Electrical Engineer with the Engineering Training Center, Shenyang Institute of Engineering. His research interest includes the fault diagnosis of power equipment.