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Design and implementation of an innovative airborne electric energy-efficient test system of fixed-wing UAV

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Abstract:

The appropriate powered configuration of the UAV (unmanned aerial vehicle) plays a vital role in improving the endurance and optimizing aerodynamic characteristics of newly designed aircraft. To realize the measurement of the parameter of the electric propulsion system in an actual flight, a novel airborne powered test scheme of the UAV is proposed and developed in this work. Both the flight test and wind tunnel experiment study are performed to assess the accuracy of the dynamic energy efficiency by examining the effect of the airspeed on the electric aircraft powered efficiency system. The results suggest that the innovatively designed scheme of the electric-powered test system is capable of implementing the measurement of the aircraft energy efficiency parameters within the error of less than 3% compared to a wind tunnel experiment. Based on the experiment of the airborne electric aircraft propulsion, it not only in favor of determining which drawbacks of the propulsion components affect the entire electric aircraft propulsion system but also can eliminate completely the influence of boundary on airflow of the conventional wind tunnel experiment, which is of high application potential for future powered efficiency optimization of fixed-wing UAVs.

Keywords:

Airborne electric-powered test system; energy efficiency; flight test; wind tunnel experiment; fixed-wing UAV (unmanned aerial vehicle);

1. Introduction

Adopting a suitable propulsion system (Motors, Propeller, ESC, batteries) for UAV capable of acquiring long-endurance performance is one of the primary goals in electric airplane design. To maximize the cruising time of aircraft, the aerodynamic optimization method [1, 2], the newly designed scheme [3-5], and the propulsion system matching [6] are usually introduced. However, in terms of research on the electric propulsion systems, there is a lack of airborne measurement equipment to respond to the efficiency parameters of the electric propulsion system. These efficiency parameters can accurately reflect the rationality of the powered configuration. Once there is a layout of the inappropriate powered components, it will affect the endurance and performance of electric aircraft,，and even threat to the safety of the vehicle due to the increase of heat energy and the penalty of the conversion efficiency of the electric aircraft propulsion system [7-9]. Therefore, it is necessary to develop an efficient test scheme to evaluate the energy efficiency index of the aircraft.

Theoretical and numerical techniques have been adopted to obtain the energy-efficient for small unmanned electric aircraft. Dahms et al. [10] presented a generic mathematical propulsion model, which could evaluate and analyze the performance of the electrical motors, propellers, and rechargeable batteries for a vertical thrusted UAS based on the statistical analysis from the numerical results. A hybrid-electric propulsion efficiency system has been investigated and evaluated for small unmanned aerial vehicles by Matlock et al [11] and Hung [12]. Donateo et al. [13] proposed a new mission-based approach to evaluate the efficiency of the whole powertrain, and showed that the efficiency of all sub-systems of the airplane were key to calculate endurance in electric flight. As shown in Ref. [14-16] and [17, 18], the effects of motor speed and incoming flow speed on the propeller efficiency and motor efficiency were studied, respectively. However, once the related research on whether the electric aircraft propulsion system is matched, the method described above will not work. Hence, it is still unknown whether it is possible to develop an airborne powered test platform of the aircraft that implements the dynamic measurement of the power system of the UAV.

To confirm a designed electric propulsion system, whether it will able to fulfill requirements in the flight condition and to verify the validity and accuracy of numerical results, a visualization experiment [19-21] is a standard method. Measurement of torque and overall efficiency of the propeller was assessed by Czyż et al. [22], who used the ASz62-IR engine of aircraft to test under training flight conditions. Verstraete et al. [23] demonstrated that the proper configuration for the motor, battery, and power management plays a crucial role in the response to dynamic load changes for small unmanned aircraft systems through hardware testing on the ground. Ma et al. [24] carried out the efficiency of an electric aircraft propulsion system research to estimate the energy consumption during the climb and the cruise phases, and the wind tunnel experiment results revealed that the proposed minimum energy consumption function method could reduce the energy consumption of the electric aircraft by over 10%. Cheng et al. [25] investigated the electrical power system efficiency based on wind tunnel testing and the self-adaptive penalty method. The results revealed that the proposed endurance model could precisely calculate the battery discharge time and describe the battery discharge process. An energy efficiency optimization method was proposed by Wang et al. [26], which could achieve reduce energy consumption by more than 10% for fixed propeller electric aircraft designed based on the results of the ground test and wind tunnel experiment. Obviously, experiments are an effective method to verify the availability of the new power design scheme of UAV. Consequently, an idea was inspired by a visual wind tunnel scheme, whether it is possible to design an airborne power efficiency system to comply the measurement and display of the efficiency parameters in real flight test cases.

This work aims to design and verify a novel airborne energy efficiency index of the aircraft, which will be capable of realizing the measure of the power system efficiency of airplane real timely. The flight test and wind tunnel experiment research are performed to evaluate the error of the dynamic efficiency measurement by discussing the impact of airspeed on the power efficiency system of the airplane. The comparison of results indicates that the newly designed efficiency system can achieve the efficiency measurement of fixed-wing UAV with an accuracy of more than at the order of magnitude of 95% in actual flight.

2. The test system of the electric aircraft propulsion

As a critical component of electric aircraft, an electric propulsion system is utilized to supply sufficient thrust for an electric airplane. There are the following main components for electric power systems such as the brushless DC motor (BLDCM), the propeller, the electronic speed controller (ESC), and the battery. Once the optimal power configuration is obtained for designing an electric airplane, it can not only realize the better energy exchange efficiency but also reduce the energy consumption of the power system. Namely, choosing an appropriate component for the propulsion system will directly affect the flight efficiency and flight stability of the aircraft. Thus, an electric propulsion system is needed to be developed for quick components efficiency verifying and constructing a new power system. In this study, an innovative airborne power test method of the UAV is proposed to achieve the high accuracy measurements of the power system parameters in a real flight.

2.1 Measurement principle of UAV powered

A network-based measuring data-processing scheme has been adopted in tests on the basis of airborne measured equipment. It acquires all basic power parameters of the aircraft in real-time conditions, including voltage, current, thrust, torque, revolutions per minute (RPM) of the motor, and airspeed, as listed in Table 1. Moreover, the efficiency parameters index of the power system, such as system output power, motor consumption power, instantaneous propeller power, propeller force efficiency and system force efficiency, motor efficiency, propeller efficiency, and system efficiency, can be derived based on the data provided by the instrumentation and Eq. (1)-(5).

Table 1. Test parameters of the UAV powered system of by airborne device

Item	Voltage	Current	Power	Thrust	Torque	RPM	Airspeed
Symbol	U	I	P	F	T	n	V
Unit	V	A	W	gf	N·m	r/min	m/s

The output power of the motor is calculated by Eq. (1), which can be defined as the quantity of the torque multiply by the rotational speed of the motor. The basic expression is Eq. (1).

$$P_{MotOut} = \frac{T \times n}{9550} \tag{1}$$

Where T and n are the torque and RPM of the motor during the cruise phase. Note that the torque of a motor T is related to its torsion f and the known arm of force l (i.e.$T = f \times l$). Similarly, the instantaneous power of the propeller is described by the thrust of the propeller times the cruise speed. The total power requirement for cruise phases is determined by the payload, which can be calculated as the product of the product of the output voltage and current of the drive circuit.

$$P_{Pro\ Ins\ Out} = F \times V \tag{2}$$

$$P_{SysOut} = U \times I \tag{3}$$

Where U and I are the out voltage and the current of the aircraft power system, and F and V represent the thrust generated by the propeller and aircraft airspeed.

To quantify indicators of the power system efficiency of the UAV during cruising, a new concept of the propeller force efficiency (PRE) and system force efficiency (SFE) is put forward, which is calculated as the ratio of the propeller thrust to the motor output power and system output power, separately. They can be calculated as

$$\zeta_{PRE} = \frac{F}{P_{MotOut}}$$
$$\zeta_{SFE} = \frac{F}{P_{SysOut}} \tag{4}$$

The efficiency of the airplane propulsion system is computed based on the data source of the test, which is expressed by taking the set of equations below:

$$\eta_{Mot} = \frac{P_{MotOut}}{P_{SysOut}}$$
$$\eta_{Pro} = \frac{P_{Pro\,Ins\,Out}}{P_{MotOut}} \tag{5}$$
$$\eta_{Sys} = \frac{P_{Pro\,Ins\,Out}}{P_{SysOut}}$$

Where η_{Mot}, η_{Pro}, and η_{Sys} denote the electric motor efficiency, the propeller efficiency, and system efficiency, respectively.

2.2 Facility and test conditions

In order to confirm the accuracy of the new proposed airborne power test system, a platform of the X-UAV fixed-wing aircraft is adopted. The engineering parameters of the airplane are given in Table 2. It can be shown that the airborne power test system is mounted at the tail of the aircraft in the coaxial with the propeller, as displayed in Fig. 1. Wherein, the major components of the electric propulsion system of the airplane, will be comprised of the propeller of GemFan 1470, the BLDCM of SunnySky X3535, and the ESC of Hobbywing SkyWalker 80A, which are illustrated in Fig.1 and detailed in the supporting materials.

Fig. 2 shows a shot of the aircraft equipped with the airborne power test system in the flight experiment. The testing is conducted at airspeed (U) of 16, 18, 20, 22 and 24 m/s correspond to the Reynolds number of 310000, 350000, 390000, 430000, and 470000, correspondingly, based on the calculated equation and mean aerodynamic chord length of 0.293 m. Then, considering the measurements within the uncertainty, the flight scheme of the same circle radius of 150 meters for 8 mins on the horizon and maintain level flight is conducted to reduce the error in the tests. Besides, the standard 6S 5200mAh battery is fully charged for the repeatability of the flight tests. The video recording the test cases is presented with the attachment Video 1. Note that all the parameters of the above Table 1 be capable of acquiring, displaying, and saving in real-time flight cases.

Table 2. Engineering parameters of the fixed-wing test aircraft

Wingspan	2000 mm	Weight	5 kg
Body Height	350 mm	Body Length	1200 mm
Wing Area	0.586 m^2	Aspect ratio	6.8
Wing load	85 g/dm^2	Chord length	293 mm

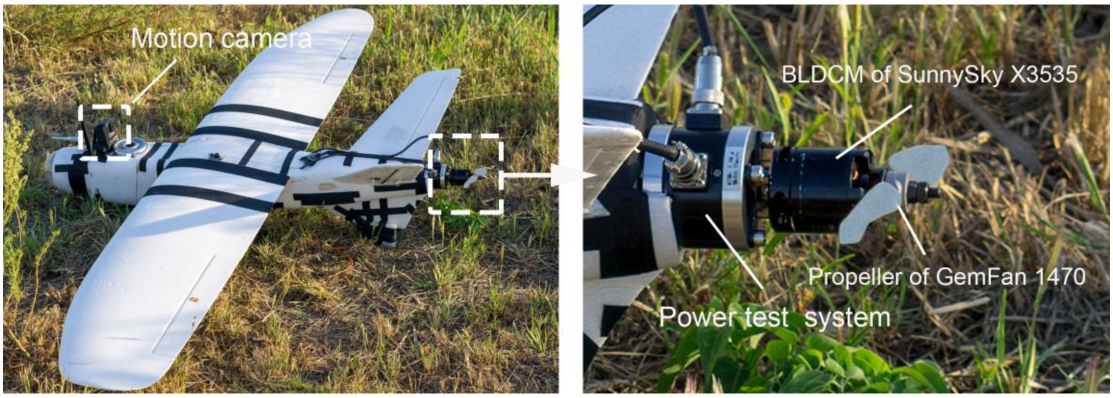


Fig. 1. The airborne power test model of a traditional fixed-wing Talon aircraft.

Fig. 2. A shot of the aircraft during the test.

To verify the accuracy of the efficiency results from the proposed airborne electric propulsion system in flight, a wind tunnel experiment is implemented in a low-speed wind tunnel numbered D1 at Beihang University. This tunnel has a cross-sectional of 1.02 m×0.76 m, the maximum wind speed in the open experimental section of 40 m/s, the turbulence intensity of nearly 0.5% for the range of test speed The power configuration of the test bench remains consistent in all tests, including the propeller, BLDCM, and ESC, as indicated in Fig. 3. The thrust of the propeller and torque generated by the motor are acquired simultaneously by using the thrust sensor and torque sensor, which are calibrated with the application of known loads before the experiment. Load accuracy has been established as 0.05% ± 20g and 0.5% ± 0.015N•M for the measurement of the thrust and torque. Wind tunnel testing has been performed under the airflow speed remains consistent with the flight cases. The data acquisition system (DAS) is adopted to carry out tasks such as the conversion of data, storage of data, the transmission of data, and processing of data in-process testing.

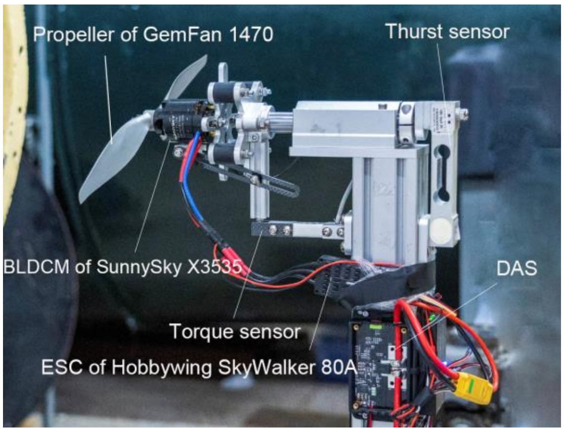


Fig. 3. The ground test of the same power configuration of UAV in wind tunnel

3. Results and analysis

Two independent experiments are conducted to compare the electrical power system parameters, including motor speed, voltage, current, thrust, and torque in the flight test and wind tunnel experiment conditions. It is a remarkable note that the above two groups of tests are the same in the component of the electric aircraft propulsion system. Table 3 shows a summary of results in terms of the range in airspeed from 16 m/s to 24 m/s. As seen the results revealed in Table 3, the flight measured data of the power system is agreed well with the wind tunnel experimental data at a single fixed velocity. The average relative error inspected is 0.32%, 0.83%, 1.17%, 0.93%, and 2.0% for the motor rotation speed, the voltage and current of the system output, the propeller thrust, and the motor torque, respectively. However, a vital difference is displayed for the electric propulsion system parameters of the UAV in the different incoming wind speeds. The results suggest that aircraft speed does have an effect on the power parameters of the airplane. Typically, it indicates that the output of the rotational speed of the electric motor, the voltage and current, the propeller thrust and motor torque increase with an increase of airflow speed.

Table 3. Summary of the impact of airspeed on power system parameters, including the flight test and wind tunnel experiment.

Item	Airspeed (m/s)	Motor speed (r/min)	Voltage (V)	Current (A)	Thrust (gf)	Torque (N·m)
Flight test	16	6435	23.8	7.9	620	0.210
Wind tunnel Exp		6420	24.3	7.8	626	0.212
Flight test	18	6831	23.7	10.2	780	0.260
Wind tunnel Exp		6780	23.8	10.1	775	0.257
Flight test	20	7242	23.7	12.5	900	0.300
Wind tunnel Exp		7250	23.9	12.3	905	0.305
Flight test	22	7820	23.6	18.1	1165	0.410
Wind tunnel Exp		7795	23.5	17.9	1157	0.400
Flight test	24	8229	23.5	24.0	1350	0.500
Wind tunnel Exp		8245	23.6	23.8	1375	0.482
Average Error (%)		0.32%	0.83%	1.17%	0.93%	2.0%

Fig. 4(a) is a similar plot of data from Table 3 of the rotational speed of the electric motor as a function of the cruise speed，which is compared with the wind tunnel experimental data from the flight tests. The results demonstrate that the device of the newly designed airborne power test system has high accuracy and low relative error below 0.8% for the measurement of the motor rotation speed. The impact of the airspeed on the rotating speed of the servo-motor increase, as the load demand of the UAV, will cause the output of the lithium-ion battery to rise. When the value of the airspeed is higher than 20 m/s, the rate of increase in motor speed has grown sharply by represented in Fig 4(a). The output power of the electric motor has been plotted in Fig. 4(b) according to the calculated results of the above Eq (1). It is consistent with the results obtained from the tests of the rotational speeds of a motor, shown in Fig. 4(a). Namely, the power consumption of the motor increases correspondingly with the increase of the incoming flow velocity due to the rise of the energy requirement of the payload. Besides, the measurement errors of the motor output power for the onboard test measurement is less than 3.6%, which is implied that the developed airborne power test system is to satisfy the engineering application requirement.

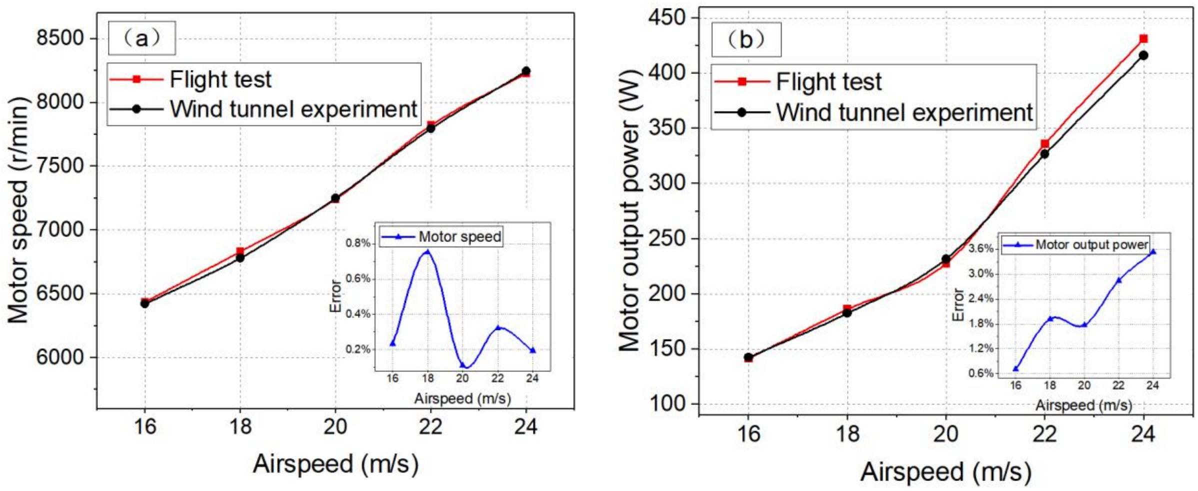


Fig. 4 Effect of airspeed on (a) the motor speed and (b) motor output power under the case of the flight test and wind tunnel experiment.

According to the theoretical calculating Eq. (2) and (3) and data from Table 3, the instantaneous power of the propeller and output power of the system is obtained. An inspection of Fig. 5(a) and (b) show that the output power of the propeller and system is increasing with the cruising speed of the airplane. In accuracy respect, the error of the measurement precision is less than 2%, which indicates that the airborne test results are in agreement with low-speed wind tunnel test data. Similar to the results of Fig. 4, the velocity can impact the instantaneous power of the propeller and the required operating power of the system effectively. However, it is interesting to note that there is a significant difference in the transformation of energy, as shown in Fig. 5. The consumption of thermal energy of the power system is larger than the motor and propeller. For example, at V= 22 m/s, the average power (average value of flight test and wind tunnel experiment) of the system output, the motor, and the propeller consumption are 423.9W, 331.1W, and 250.5W, and efficiency of power conversion of 59.1%, 78.1%, and 75.7%, respectively. It is clear that the requirement energy of the motor is provided from the system output to drive the rotation of the propeller. Such phenomenon can be explained as the result of the increasing multi-stage transmission incurring larger thermal energy losses at the propulsion system.

The configuration of the electric propulsion system of airplane during tests,

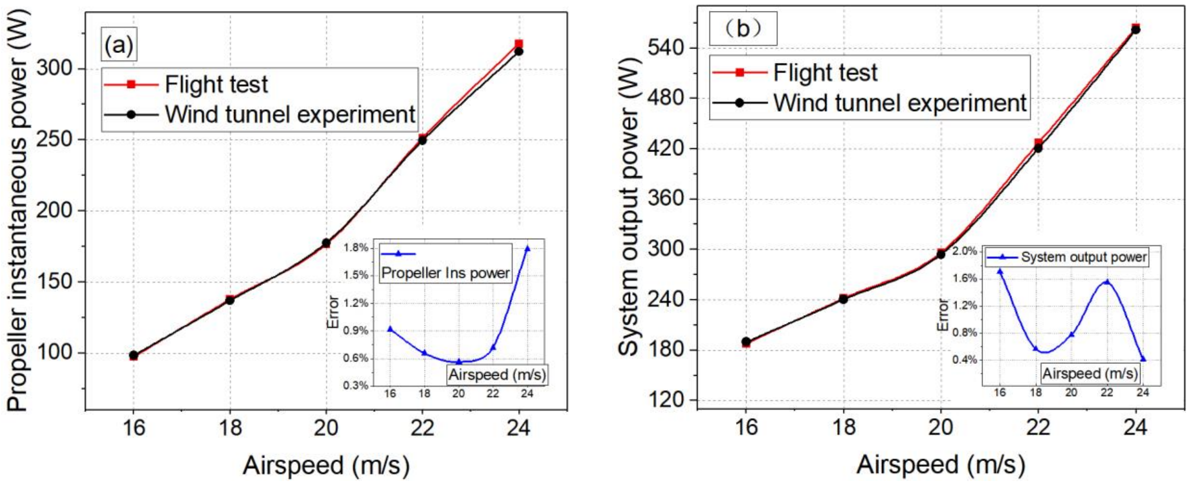


Fig. 5. Effect of airspeed upon (a) the propeller instantaneous output power and (b) system output power under the case of the flight test and wind tunnel experiment.

To reveal the performance parameters of propeller and system of UAV, the conceptions of propeller force efficiency and system force efficiency are proposed by the Eq. (4). The unit for force efficiency is gf/ W that the value of the pull force under per unit power for a specific machine. It can be explained that if the value has higher numbers will imply better performance. A comparison of these results presented in Fig. 6 shows that the test airspeed is a significant parameter for the electric power system of UAV. The force efficiency of the propeller and the system decrease with an increasing airspeed under the current experimental conditions, which demonstrate the lower airspeed can be in favor of enhancing the work efficiency of the propeller and the system. However, the greater speed will deteriorate the energy conversion efficiency of the electric propulsion system. It is mainly caused by laminar-turbulence transition around the surface of the propeller and the wing, eventually, results in increasing the drag and decreasing both the parameters of the force efficiency. Otherwise, in Fig. 6, the force efficiency of the propeller is larger than the system force efficiency under the error in the measures less than 3%, which exhibits the multiple transmission capable of weakening the efficiency of power conversion. Notably, at V=20 m/s, the force efficiency of the system decreases sharply, and there may be flow separation on the upper surface of the propeller and wing. It leads to the increasing amplitude of the aerodynamic drag is larger than the thrust of the propeller.

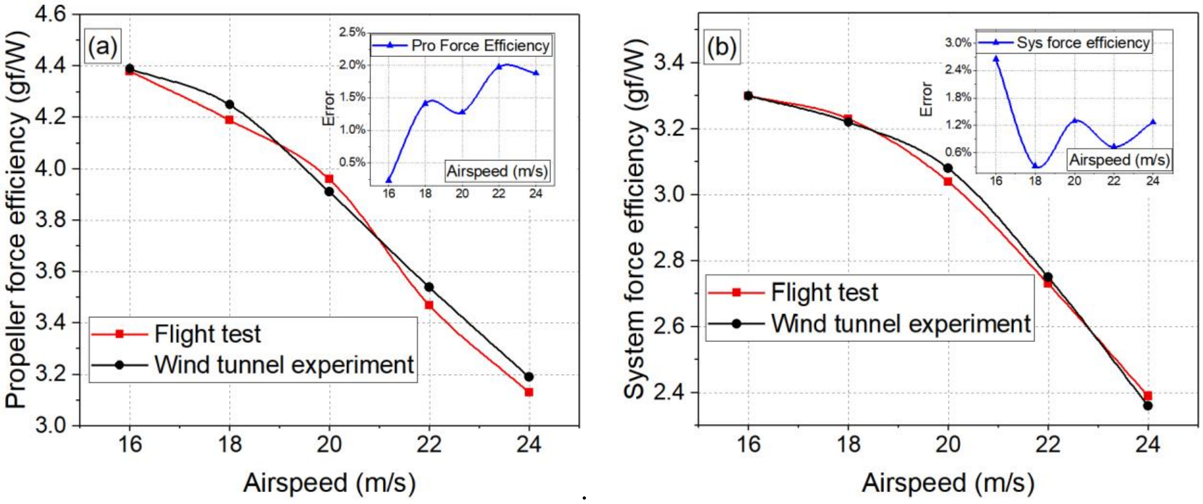
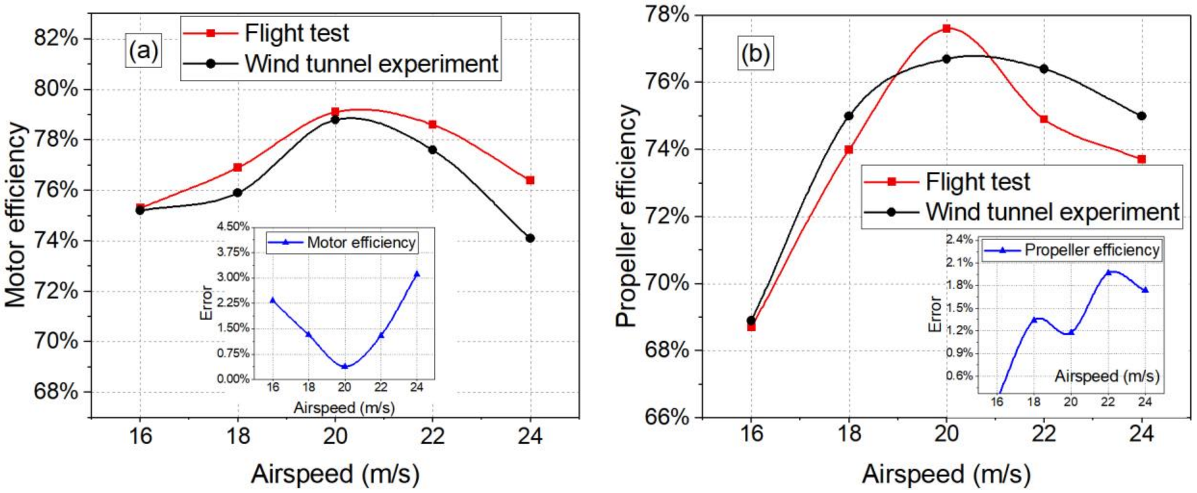


Fig. 6. Comparing the flight measurement results with the wind tunnel experiment, (a) propeller force efficiency, and (b) system force efficiency versus airspeed.

As seen in Fig. 7, the efficiency of the motor, the propeller, and the system in the airborne electric power system are computed and summarized based on the data of reference Table 3 and the aforementioned Eq. (5). It can be seen that, for one thing, compared with the wind tunnel experiment, the results of the flight test are identical within 3% of the uncertainty of measurements. Furthermore, the variation tendency of the three types of efficiency parameters is almost consistent. That means that the rate of the calculated efficiency characteristic curve of the aircraft first increases against airspeed until reaching 20 m/s where the rate then decreases. In Fig. 7, the rate of efficiency of the motor, the propeller, and the propulsion system increase when airspeed increases because the duty cycle of Pulse Width Modulation (PWM) gradually increases, which until attains the peak efficiency design of electric power system. However, the rate of efficiency falls after this point V= 20 m/s because the thermal efficiency fell while the increase of the output power of the electric propulsion system.



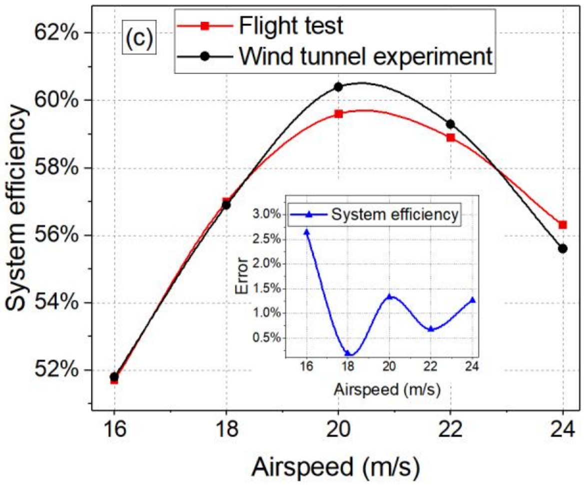


Fig. 7. Comparing the flight measurement results with the wind tunnel experiment, (a) motor efficiency, (b) propeller efficiency, and (c) system efficiency as a function of airspeed.

4. Conclusions

In the present work, a novel designed airborne electric propulsion test system of the fixed-wing UAV is put forward and developed, which ensures that the energy-efficient power system of aircraft can be measured real timely with high-accurate. A series of flight evaluations are performed to investigate the practical application and reliability of the newly devised airborne efficiency measuring system at an airspeed ranging from 16 m/s to 24 m/s. To verify the precise of the real-time measurement system of UAV in flight, a wind tunnel experiment is conducted by adopting the same configurations of the electric aircraft propulsion system in flight, such as the propeller, the BLDCM, and the ESC.

The results indicates that the first propose of the dynamic powered test system of UAV could be applied to analysis (I) the output power of the electric motor, the propeller, and the airplane power system, (II) the force efficiency of the propeller and the aircraft propulsion system, and (III) the efficiency of the electric motor, the propeller, and the electric power system. It will be of benefit to find out which shortcomings of the powered components affect the entire electric aircraft propulsion system. Additionally, the interference of the support surface, the influence of boundary on airflow in the wind tunnel experiment, can be eliminated fully by adopting the designed scheme of the airborne electric test system. Finally, the comparison wind tunnel results confirm that the airborne energy efficiency test system of fixed-wing UAV can be obtained with an accuracy of more than at the order of magnitude of 95% with real flight tests, which is potentially promising for electric aircraft powered optimization.

Conflict of interest statement

There is no conflict of interest.

Acknowledgments

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