A Simple Method for Studying Aero-Propulsion Characteristics of a Distributed Electric Propulsion Aircraft

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Abstract. Distributed electric propulsion (DEP) is a popular research area in the aerospace field, with most research focusing on investigating the aerodynamic features of DEP configurations through numerical simulations. However, little has been done to optimize the coupling of distributed power and airframe. This paper starts with a problem of the propeller/wing aero-propulsion characteristics and a multidisciplinary analysis framework for electric aircraft, followed by a simplified aerodynamic analysis method for the propeller/wing aero-propulsion analysis. The geometric model of placing a propeller at the leading edge of a wing was analyzed using the RANS method for aerodynamic analysis, and the results were compared with those of the simplified aerodynamic analysis method to validate the rationality of the simplified analysis method. The model established in this paper was used for aerodynamic analysis, aerodynamic optimization design, and electric propulsion system parameter analysis of typical distributed electric propulsion aircraft. This provides valuable reference for the design of distributed electric propulsion aircraft.

Keywords: Distributed Electric Propulsion · Multidisciplinary Framework · Vortex Lattice Method · Actuator Disk Theory · Electric Propulsion System

1 Introduction

The electric propulsion system for aircraft refers to a propulsion system that uses electric energy as the source of propulsion, and includes all-electric, hybrid electric propulsion technology. The energy forms used in electric aircraft include solar photovoltaic, fuel cells, batteries, and hybrid systems. The configuration of electric propulsion can be divided into two main types: centralized and distributed, usually utilizing propellers and ducted fans as the propulsion devices. Among many concepts of electric aircraft propulsion technology, distributed electric propulsion technology (DEP) is currently one of the most popular research areas.

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When distributed electric propulsion technology is applied to aircraft, the aerodynamic characteristics of the aircraft and the propulsion system are strongly coupled, requiring exploration of their aerodynamic and propulsion coupling characteristics from multiple perspectives. The engineering experience-based aircraft conceptual design and aerodynamic analysis methods are no longer suitable for the early design of distributed electric propulsion aircraft.

In recent years, many researchers have conducted research on the design and analysis methods of distributed electric propulsion aircraft. Yang Wei et al. [1] conducted aerodynamic analysis on a distributed electric propulsion aircraft considering the influence of propeller slipstream and optimized the distributed electric propulsion configuration using particle swarm optimization algorithm. Rao Chong [2] conducted aerodynamic analysis on a typical distributed electric propulsion aircraft under takeoff and landing conditions as well as cruise conditions and obtained the conclusion that the aerodynamic efficiency of the aircraft can be improved when the rotation direction of the propeller at the wingtip is opposite to the direction of the wingtip vortex. Cheng Zhiyong et al. [3] established a rapid evaluation method for the aerodynamic characteristics of a distributed electric propulsion aircraft based on the vortex lattice method and validated it by using high-precision solution methods. Lei Yao [4] compared the computational fluid dynamics (CFD) results with wind tunnel test results to investigate the influence of propeller slipstream on the aerodynamic characteristics of wings and the effect of wings on propeller performance parameters. The SUAVE development team utilized the Python programming language to construct a specialized framework for aircraft conceptual design. Based on this framework, they performed analysis [5] and optimization [6] of distributed electric propulsion aircraft. Ma Yiyuan et al. established an electric aircraft conceptual design method [7] and a multi-disciplinary optimization design framework [8] based on a distributed electric propulsion aircraft with 24 electric ducted fans. Zhang Xingyu et al. conducted ground-based [9] and wind tunnel experiments [10] on a DEP aircraft, from which they obtained some aerodynamic-propulsion coupling characteristics.

In the pursuit of enhancing aircraft performance, the aerodynamic interaction between the wing and the propeller has been extensively studied. To realistically simulate this interaction, numerous high-precision numerical simulations based on the Navier-Stokes equation have been conducted for Distributed Electric Propulsion (DEP) aircraft. However, the costly mesh generation, large matrix inversions of state variables and post-processing involved in these solutions have hindered the investigation into the aerodynamic characteristics of DEP aircraft. As a result, moderate-accuracy aerodynamic analysis methods have emerged as a leading-edge approach to DEP aircraft design.

Therefore, the main contents of this article are as follows. In the second part, a multidisciplinary framework for electric aircraft is established, which includes the electric propulsion system model and the aero-propulsion coupling model. In the third part, the aero-propulsion coupling analysis method is validated to ensure the accuracy of the model calculations. In the fourth part, the method is used to carry out aerodynamic analysis, aerodynamic optimization design, and electric propulsion system parameter analysis for typical distributed electric propulsion aircraft. Finally, a conclusion is presented in the fifth part.

2 Methodology

2.1 Multidisciplinary Analysis Framework for Electric Aircraft

The components of the electric propulsion system have the advantages of small size, light weight, simple structure, and high efficiency. According to the scale independent characteristics of the electric propulsion system, a more optimal design can be achieved by using a distributed electric propulsion configuration, such as using the slipstream effect of the distributed propeller and boundary layer ingestion (BLI) technology to improve the aerodynamic efficiency of the aircraft. The distributed electric propulsion technology has great potential for development and can achieve higher energy efficiency than fuel-powered aircraft.

The biggest difference between electric aircraft and conventional aircraft is the difference in energy framework, so a new energy system framework needs to be established for electric aircraft. The modeling framework for electric aircraft is shown in Fig. 1, and a typical distributed electric propulsion aircraft is shown in Fig. 2.

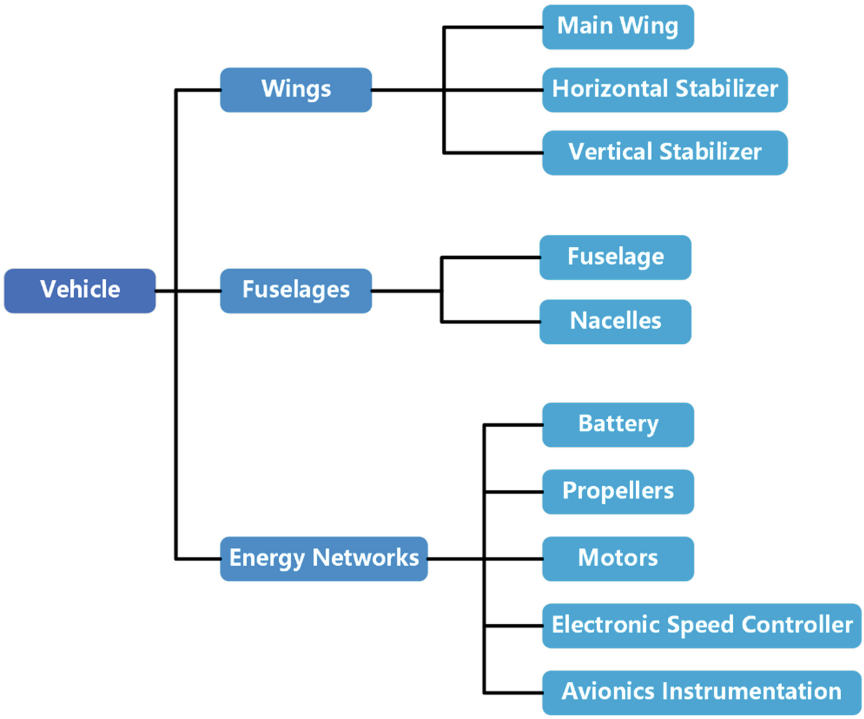


Fig. 1. The modeling framework for electric aircraft

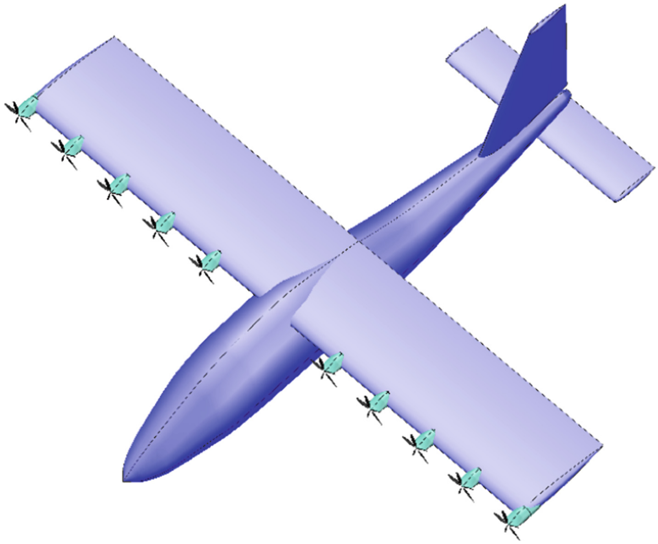


Fig. 2. A typical distributed electric propulsion aircraft

2.2 Modeling of Electric Propulsion System

The combination of all components that provide power to the aircraft is referred to as the electric propulsion system of the aircraft. The energy system framework of an all-electric aircraft is relatively simple, consisting of battery, motor, motor controller, and propeller [11]. The diagram of the framework is shown in Fig. 3. The green line in the figure represents electrical energy flow, and the red line represents mechanical energy flow. The motor converts electrical energy into mechanical energy, which drives the propeller to rotate.

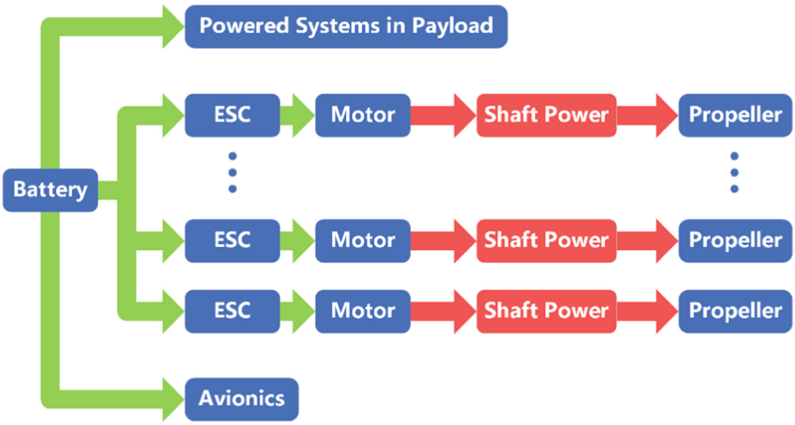


Fig. 3. Energy system framework for electric aircraft

Model for Lithium-Ion Battery Discharge. The key to any electric propulsion system is energy, which can come from a battery, fuel cell, or electricity generated through a generator. For a typical lithium-ion battery, we use an empirical battery discharge model for modeling.

$$f = 1 - \exp(-20x) - \exp(-20(1-x)) \tag{1}$$

$$R = R_0(1 + C \cdot f) \tag{2}$$

$$P_{\text{discharge}} = I^2 \cdot R \tag{3}$$

Here, x represents the charging status of the battery, R_0 is the reference internal resistance, and C is the discharge rate of the battery.

Motor Model. Approximately modeling the propulsion motor as a brushless DC motor, this article employs an empirically corrected first-order model to analyze the performance of the brushless DC motor. The equivalent internal circuit model of the DC motor is shown in Fig. 4.

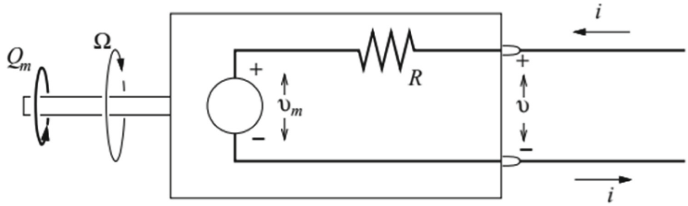


Fig. 4. Equivalent circuit for a DC electric motor

Assuming that the motor's resistance R is constant and that the torque on the shaft is linearly related to the current.

$$Q_m(i) = (i - i_o)/K_Q \tag{4}$$

Assuming that the internal counter-electromotive force of the motor is equal to the ratio of the motor speed to the motor speed constant, the motor's terminal voltage can be obtained.

$$v_m(\Omega) = \Omega/K_V \tag{5}$$

$$v(i, \Omega) = \Omega/K_V + iR \tag{6}$$

Based on the above equations, the motor's current, torque, shaft power, and efficiency can all be expressed as functions of the motor's speed and terminal voltage.

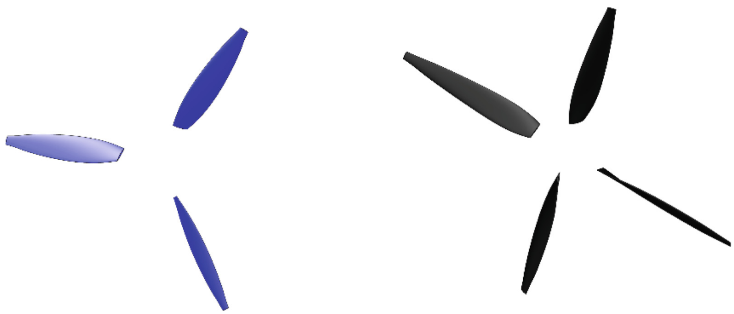
$$i = \left(v - \frac{\Omega}{K_V}\right)\frac{1}{R} \tag{7}$$

$$Q_m = \left[\left(v - \frac{\Omega}{K_V}\right)\frac{1}{R} - i_o\right]\frac{1}{K_Q} \tag{8}$$

$$P_{shaft} = Q_m \Omega \tag{9}$$

$$\eta_m = \left(1 - \frac{i_o}{i}\right)\frac{K_V}{K_Q}\frac{1}{1 + iRK_V/\Omega} \tag{10}$$

Propeller Model. The geometry of the propeller model is quite complex, and it requires consideration of many parameters. Therefore, a fast and optimal method for designing propellers [12] was used to develop a propeller design function, which enables quick modeling and estimation of multidisciplinary parameters. In the program, the propeller's design-level parameters were entered to obtain chord and twist distributions along the radius of the propeller and to determine the propeller's geometry. Then, using the simplified aerodynamic analysis method established later in the text, the performance parameters of the propeller were obtained. A three-bladed propeller and a four-bladed propeller were designed according to this method, and their geometric models in OpenVSP [13] are shown in Fig. 5.



(a) Three-bladed propeller (b) Four-bladed propeller

Fig. 5. Propeller model displayed in OpenVSP

2.3 Propeller/Wing Aero-Propulsion Coupling Model

The analysis of the aero-propulsion coupling characteristics involves the use of the vortex lattice method to analyze the wing's aerodynamics. However, the propeller's complex geometrical properties require simplification. Two common methods of simplification involve reducing the propeller to an approximation of the actuator disk model and reducing the geometrical surface information to that of the different radially positioned blade elements.

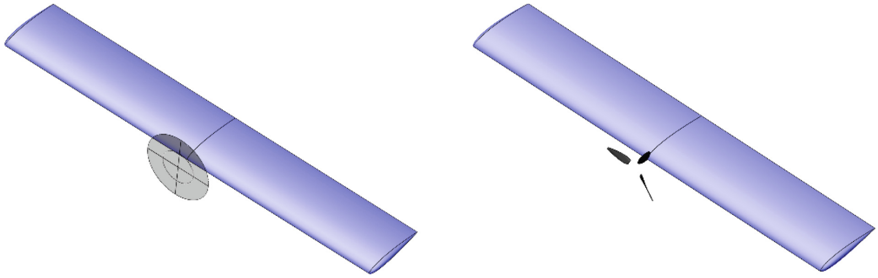
The resulting propeller-wing interaction model is a superposition of several basic models in which the spatial positions of the propeller blade vortex system and the propeller wake vortex system change constantly with time. This method of analysis is known as the Unsteady Vortex Lattice Method (UVLM), whereas the actuator disk theory and wing related vortex system do not change with time. The basic model is shown in Table 1.

Table 1. Propeller/wing aero-propulsion coupling model

Basic Models	Detailed Explanations
Actuator disk model	Based on the momentum theory of propellers, the propeller is simplified to a thin disk, which approximates the axial and tangential velocity changes
Propeller blade vortex system	The blade of the propeller is discretized using a non-planar vortex lattice method, with horseshoe vortices placed in the grid for unsteady numerical solution
Propeller wake vortex system	The fixed propeller wake vortex system on the propeller vortex surface is used to simplify the analysis of the propeller wake
Wing surface vortex system and source sink vortex system	The wing is discretized using a non-planar vortex lattice method, with horseshoe vortices placed in the grid for steady numerical solution
Wing wake vortex system	In the wake after the wing, near the wing trailing edge, it is approximately a quadratic parabola, while the far wake region tends to be aligned with the direction of far-field inflow

Aerodynamic Analysis Model Based on ADT/VLM. The aerodynamic analysis model of the Actuator Disk Model /Vortex Lattice Method (ADT/VLM) involves superimposing several basic models, comprising the actuator disk model, the wing surface vortex system, the wing source-sink system, and the wing wake vortex system, as shown in Fig. 6(a). The actuator disk model simulates the effect of the propeller on the aerodynamics, with the changing wake blowing into the wing and creating a slipstream effect on it.

Aerodynamic Analysis Model Based on UVLM/VLM. The Unsteady Vortex Lattice Method (UVLM)/Vortex Lattice Method (VLM) aerodynamic analysis model involves superimposing several basic models, comprising the propeller blade vortex system, the propeller wake vortex system, the wing surface vortex system, the wing source-sink system, and the wing wake vortex system, as shown in Fig. 6(b).



(a) ADT/VLM (b) UVLM/VLM

Fig. 6. Propeller/wing aero-propulsion coupling model

3 Aerodynamic Verification and Validation of the Model

3.1 Model Description

Establish a model for method validation, as shown in Fig. 7. The model consists of a straight wing and a propeller. The wing has a span of 9.6 m, a mean geometric chord of 1.6 m, and a NACA2412 airfoil. Based on Robert H.L's proposed method for propeller rapid design, the geometric model of the propeller is obtained with a design thrust of 1250N, a designed lift coefficient of 0.7, and a design speed of 2500 RPM. The propeller has three blades, a tip radius of 0.8 m, a hub radius of 0.2 m, and is located 0.3 m in front of the wing leading edge. The analysis is conducted at an altitude of 2500 m and a Mach number of 0.226. The accuracy of the method is validated by comparing simplified aerodynamic analysis results with those obtained from RANS methods.

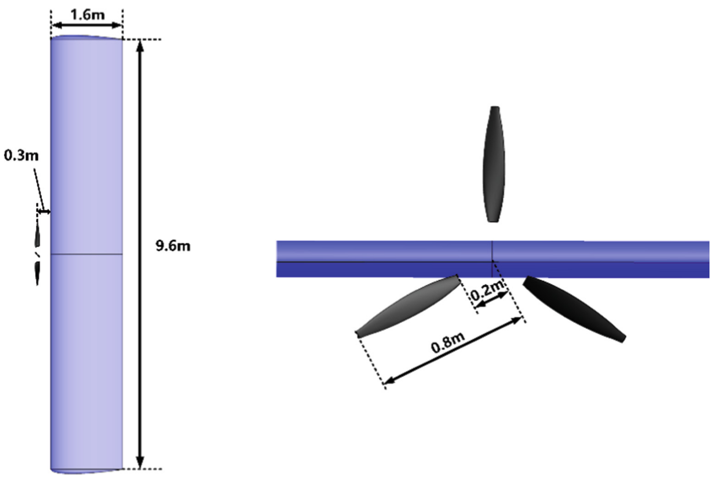


Fig. 7. Geometry model for verification and validation

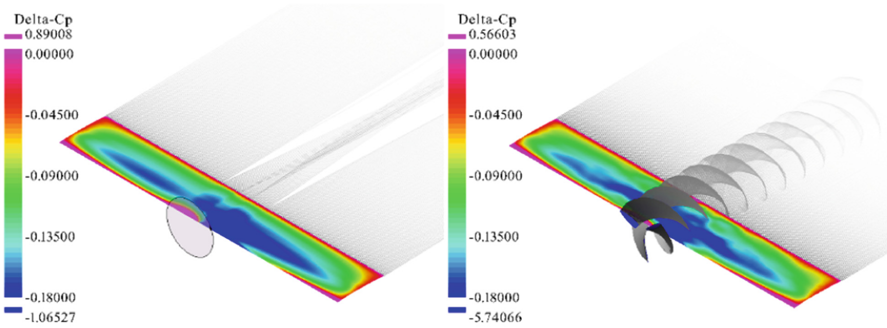
3.2 Verification and Validation

First, method validation was performed on a single three-bladed propeller. The results from the simplified aerodynamic analysis method were compared to those from the RANS method and the comparison is demonstrated in Table 2. The simplified aerodynamic analysis method was found to predict the propeller performance with an error in thrust not exceeding 10% and an error in torque not exceeding 5%, indicating a strong level of accuracy compared to the predictions obtained from the RANS method.

Table 2. Comparison of results of two solvers

Solver	Thrust	Difference	Torque	Difference
RANS	1416.38N	7.37%	484.34 Nm	4.71%
OpenVSP	1520.81N		507.17 Nm	

Afterwards, the previously defined model was subjected to method validation, and the results presented in Fig. 8. It is evident that the simplified aerodynamic analysis method can effectively replicate the impact of the propeller slipstream on the wing. Consistent pressure distribution outcomes were obtained by applying the RANS method, as depicted in Fig. 9, demonstrating the same regularity.



(a) Result of ADT/VLM model (b) Result of UVLM/VLM model

Fig. 8. Results of simplified aerodynamic model: the pressure coefficient distribution

The comparison between the results obtained from the simplified aerodynamic analysis method and the high-precision aerodynamic analysis method is presented in Table 3. The results reveal that the aerodynamic analysis method of ADT/VLM can effectively simulate the increment of slipstream, consistent with the results generated by the high-precision method, whereas the simulation effect of UVLM/VLM is relatively poor. Moreover, the input values of the thrust coefficient and power coefficient for the actuator disk model in this case are obtained from the numerical simulation of non-steady vortex lattice method of the propeller. So in the process of numerical simulation of propeller slipstream, it is recommended to first obtain the input values of thrust coefficient and power coefficient based on unsteady vortex lattice method or experimental data, and then use the ADT/VLM model to simulate the increment of slipstream, to achieve better analysis results.

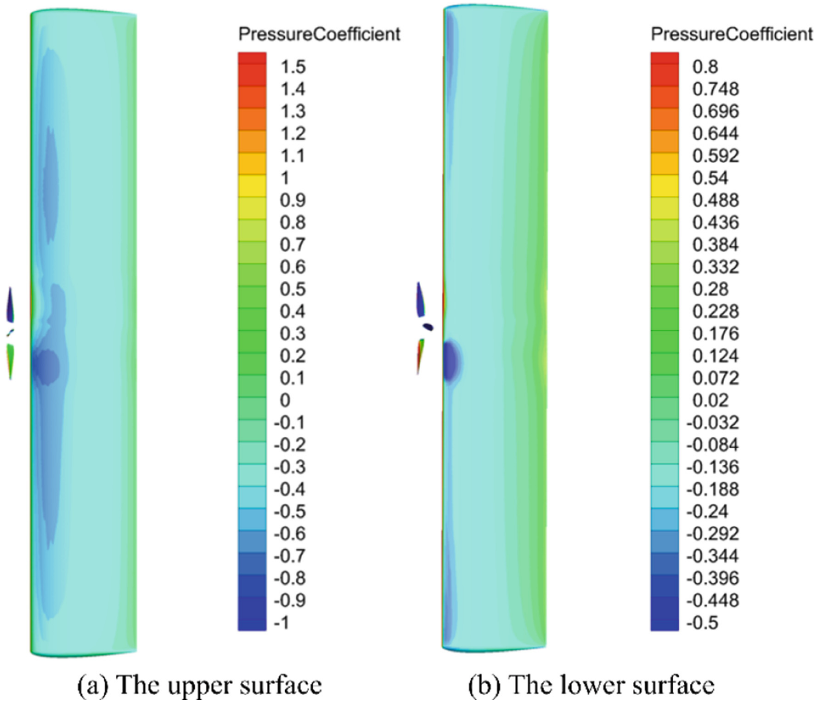


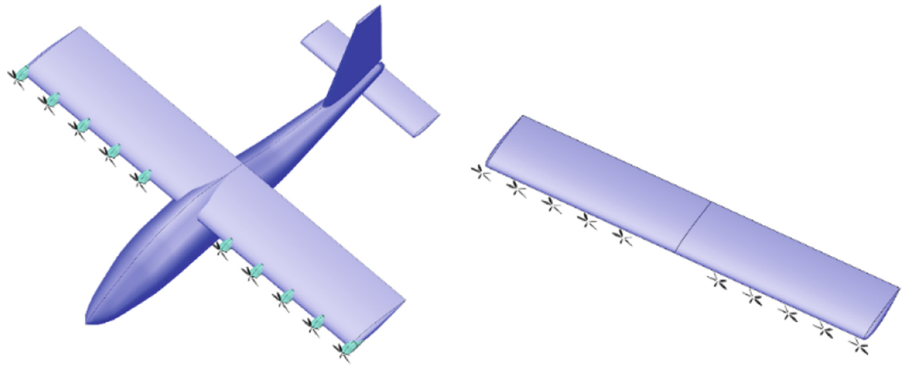
Fig. 9. Pressure coefficient distribution for the wing/propeller configuration

Table 3. Comparison of the results

Solver	Thrust	Torque	Wing/Prop CL	Clean Wing CL	Delta
RANS	1533.4N	509.2N	0.2513	0.2463	2.03%
ADT/VLM	–	–	0.2379	0.2334	1.93%
UVLM/VLM	1528.5N	510.3N	0.2339	0.2334	0.21%

4 Case Studies

In order to delve deeper into the aero-propulsive coupling characteristics of distributed propeller layouts, a simplified aerodynamic analysis method was employed to analyze a distributed electric propulsion configuration, illustrated in Fig. 10. The wing has a span of 9.6 m, a chord length of 1.6 m, no twist angle, and a NACA2412 airfoil. Ten propellers, each with five blades, are positioned 0.2 m from the leading edge of the wing.



(a) DEP aircraft used for calculation (b) DEP configuration for aero-propulsion analysis

Fig. 10. A distributed electric propulsion configuration used for research

4.1 Research on the Different Rotating Direction of Distributed Propellers

The aero-propulsive coupling characteristics of the distributed electric propulsion aircraft are analyzed under the given flight conditions. This section analyzes the configurations of four different rotation combinations, as shown in Fig. 11.

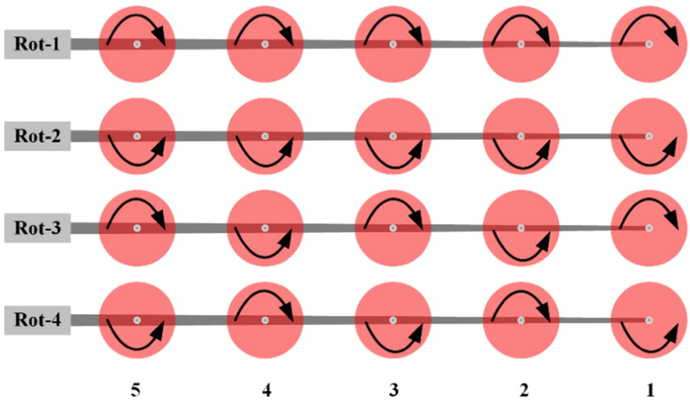


Fig. 11. Different propeller rotation combinations

The comparison of spanwise lift coefficient distribution and pressure coefficient distribution of the wing for four different propeller rotation combinations at an angle of attack of 2° is shown in Figs. 12 and 13. The local angle of attack increases, and the lift coefficient and pressure coefficient increase when the propeller rotates in the direction of upward rotation, and vice versa. At an angle of attack of 2°, both Rot-1 and Rot-3 show a significant increase in lift and a decrease in drag, with Rot-1 performing better. The drag of Rot-2 and Rot-4 both increase, and the increase in lift is not significant.

The results also reveal that the wing tip propeller has the most significant effect on the wing lift and drag. Additionally, the wingtip propeller rotating in the opposite direction to the wing-tip vortex rotation can increase lift and decrease drag.

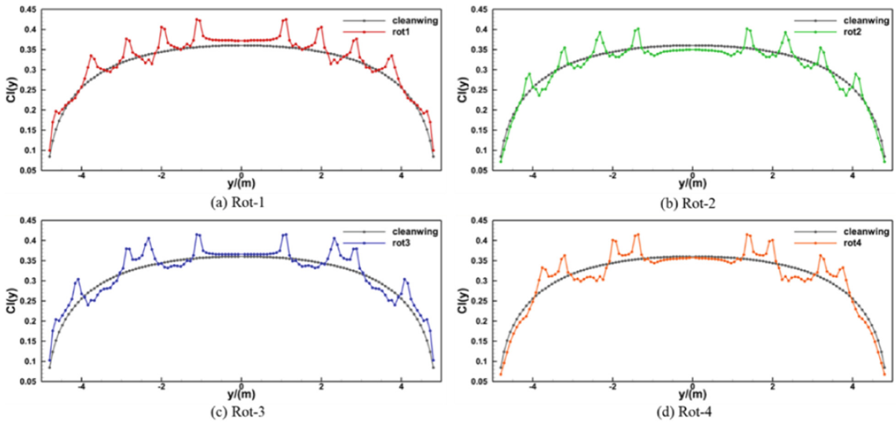


Fig. 12. The distribution of lift coefficient

4.2 Aerodynamic Optimization Design

Optimization design was conducted for the configuration of the distributed propeller under the cruising condition of the aircraft. The optimization result shows that only placing two large propellers at the wingtips and making them rotate in the opposite direction of the wingtip vortices can achieve higher lift-to-drag ratio in the cruising condition. This conclusion verifies the design concept of the X-57 Maxwell aircraft. The results show that the lift-to-drag ratio can be improved by 14.72% after optimization. The comparison of optimization results is shown in Table 4, and the comparison of pressure coefficient distribution is shown in Fig. 14. As can be clearly seen from the figure, the optimized result has more low-pressure areas compared to before optimization, and therefore has better lift-to-drag characteristics.

4.3 Analysis of Electric Propulsion System Parameters

This section analyzes the parameters of the electric propulsion system. The typical flight profile is shown in Fig. 15, and the specific parameters for general aviation aircraft are shown in Table 5.

The time-varying curves of various parameters of lithium-ion battery throughout the flight profile are shown in Fig. 16.

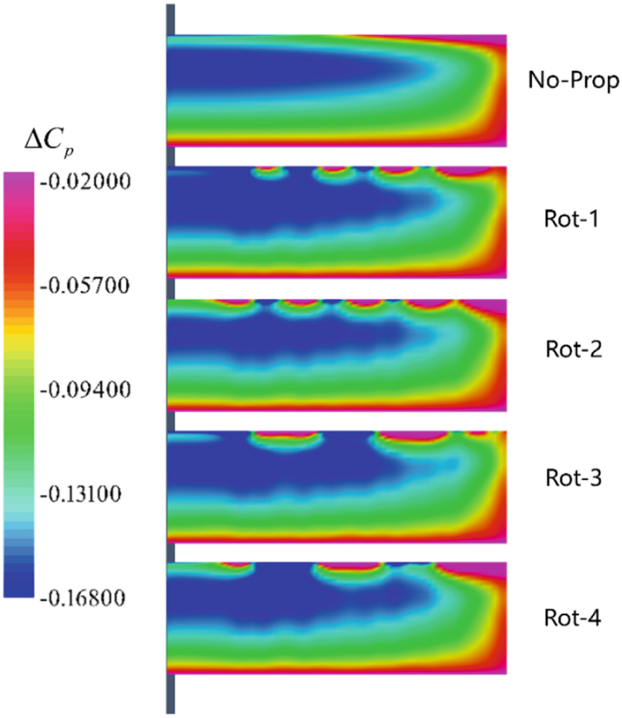


Fig. 13. The distribution of pressure coefficient

Table 4. Optimization result

Parameter	Clean Wing	Baseline	Opt	Delta
CL	0.2344	0.2439	0.2631	7.87%
CDi	2.99e−3	2.52e−3	1.98e−3	−21.43%
L/D	22.72	24.26	27.83	14.72%

The results show that during the high output power stage of the battery, the slope of the corresponding energy change curve and SOC change curve is greater. In the voltage of the battery curve, and the open circuit voltage represents the ideal voltage of the battery, while the under-load voltage represents the actual terminal voltage of the battery. In the battery C-Rate curve, there are two curves that show the nominal C-Rate and the instantaneous C-Rate changing with time. The nominal C-rate is often considered as a parameter when selecting the battery. However, when considering issues such as deep discharge and battery life, the instantaneous C-rate is an important indicator. The current curve satisfies the basic relationship where power equals voltage multiplied by current.

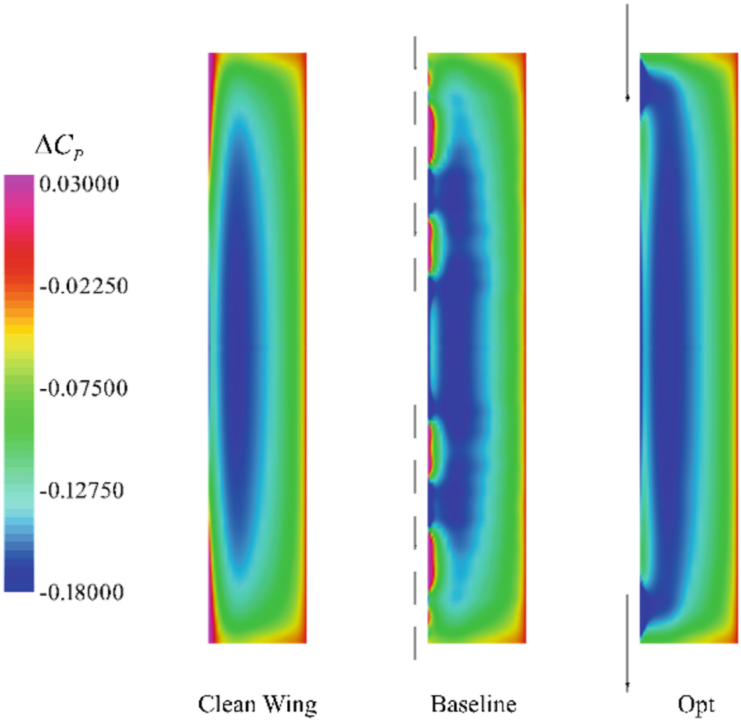


Fig. 14. Optimization Result: The distribution of pressure coefficient

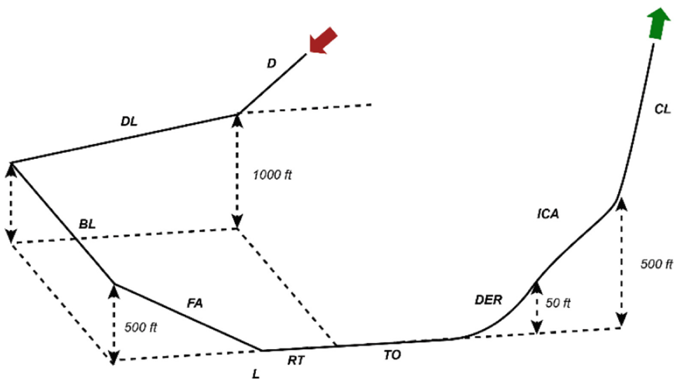


Fig. 15. Typical flight profile.

Table 5. Parameter settings of each segment of the flight profile

Segment	Symbol	Height	Velocity
Departure End of Runway	DER	0–15 m	39–42.9 m/s
Initial Climb Area	ICA	15–500 m	42.9–60 m/s
Climb	CL	500–2000 m	60–78 m/s
Cruise	CR	2000 m	78 m/s
Descent	D	2000–300 m	78–50.7 m/s
Downleg	DL	300 m	50.7–46.8 m/s
Baseleg	BL	300–150 m	46.8–42.9 m/s
Final Approach	FA	150–0 m	42.9–39 m/s

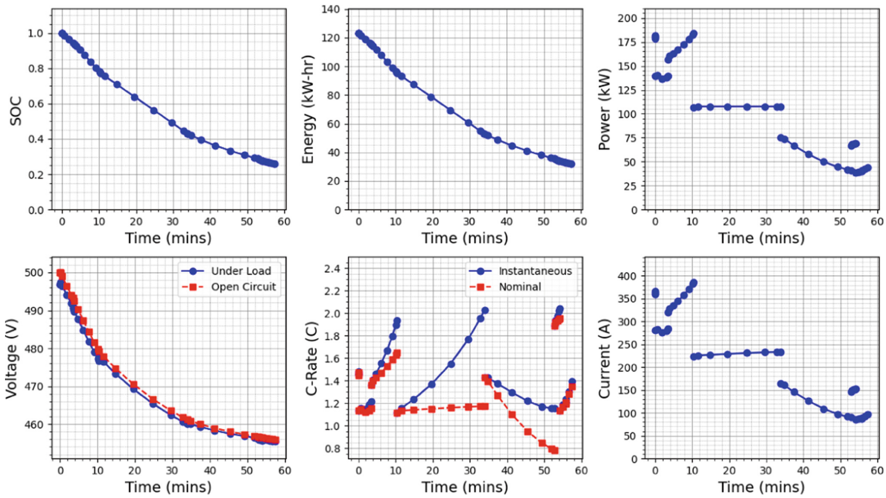


Fig. 16. Battery pack conditions

5 Conclusions

In order to improve the design efficiency of electric aircraft, this paper proposes a method for analyzing the aero-propulsive coupling characteristics of distributed electric propulsion aircraft. The following conclusions are drawn:

(1) The method constructs a framework for the distributed electric propulsion aircraft and establishes a preliminary model for the electric propulsion system, including the discharge model of the battery, the brushless DC motor model, and the propeller model.

(2) Based on the potential flow theory, a simplified aerodynamic analysis method is established to analyze the aero-propulsive coupling characteristics between the propeller and the wing. The accuracy of the method is verified by comparing it with the results based on the RANS method.
(3) The simplified aerodynamic analysis method is used to perform aerodynamic analysis and optimization design of the distributed electric propulsion aircraft, and optimal results are obtained.
(4) The typical flight profile of the aircraft is established, and this method is used to analyze the electric propulsion system parameters of the distributed electric propulsion aircraft, obtaining the performance changes of the aircraft energy system throughout the flight profile, and verifying the practicality of the method.

This method can quickly obtain performance parameters for distributed electric propulsion aircraft, laying a research foundation for conducting more detailed research and optimization design of distributed electric propulsion aircraft power distribution architecture in the future.

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