Flight Performance Estimation of eVTOL Aircraft Using Synthesis of Aerodynamics Theories of Rotorcraft and Fixed-Wing Aircraft

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(Received 15 January 2024; revised 20 February 2024; accepted 22 February 2024)

Abstract: This paper developed a synthesis process based on the aerodynamic theories of rotorcraft and fixed-wing aircraft to estimate the performance of electric vertical takeoff and landing (eVTOL) aircraft, which commonly adopt multiple rotors for vertical flight, and propeller and wing for forward flight. Momentum theory analysis and blade element analysis have been well used to analyze flight performance of rotor and propeller. Using the synthesis theory, this study investigated flight performance of 12 eVTOL aircraft including multicopter, lift & cruise, and vectored thrust categories. Flight profiles of driving motor, rotor, and airframe at hovering, climb and descent, and forward flight were estimated. It was also indicated that specifications of the electric propulsion system were defined to match the propeller or rotor to satisfy the flight mission.

Key words: electric vertical takeoff and landing (eVTOL) aircraft; advanced air mobility; rotor; fixed-wing; flight performance; aerodynamic theory

CLC number: V212 **Document code:** A **Article ID:** 1005-1120(2024)01-0035-08

0 Introduction①

Advanced air mobility (AAM), which is one of highly convenient and environment friendly means of transportation, has been attracting a great deal of attention worldwide since the middle of 2010s. The advantages of electric vertical takeoff and landing (eVTOL) aircraft as a means of airborne transportation, such as rapid mobility, zero emissions, and low noise, have attracted much attention. Various research and development efforts related to eVTOL aircraft have been conducted, and about 1 000 projects have been proposed by about 350 companies and startups up to now according to the eVTOL news[1].

Aerodynamic problems are often analyzed using aerodynamic theories, numerical simulation and experiments. In most cases of conceptual and preliminary aircraft designs, we do not concern about details of aerodynamics or propulsion, while aerodynamic theories and statistical formulae are well used to estimate aerodynamic forces.

NASA design and analysis of rotorcraft (NDARC), which is a conceptual/preliminary design and analysis code for rapidly sizing and conducting performance analysis of new aircraft concepts, was developed and applied to the eVTOL aircraft by NASA[2]. Bacchini and Cestino[3] evaluated performances of the three main eVTOL configurations by estimating five main parameters, the energy and the time required to satisfy specified missions. There are also many studies using computational fluid dynamics (CFD), such as Tanabe et al.[4] and Murphy et al[5]. On the other hand, most methods

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①Presented at the 9th Asian/Australian Rotorcraft Forum (ARF) and the 5th International Basic Research Conference on Rotorcraft Technology.

How to cite this article: LEI Zhong. Flight performance estimation of eVTOL aircraft using synthesis of aerodynamics theories of rotorcraft and fixed-wing aircraft[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2024, 41(1): 35-42.

http://dx.doi.org/10.16356/j.1005-1120.2024.01.002

are difficult and time consumed to calculate performance of the eVTOL aircraft.

Recently, Ref.[6] developed a synthesis process, which was coupled by both of aerodynamic theories of the rotorcraft and fixed-wing aircraft, and applied this tool to analyze and compare flight performance of several eVTOL aircraft under research and development. Aerodynamic theories and statistical formulae were used to estimate performance of airframe, and then it was also extended to estimate requirements of propulsion systems. This synthesis process largely simplifies work and reduces computation time in conceptual and preliminary designs of the conventional and unconventional types of aircraft, including the eVTOL aircraft. This paper provides a review of the synthesis theory for the eVTOL aircraft, and shows some results of application. Three categories as shown in Fig.1, including 12 eVTOL aircraft investigated to estimate flight performance and requirements of the electric propulsion system.

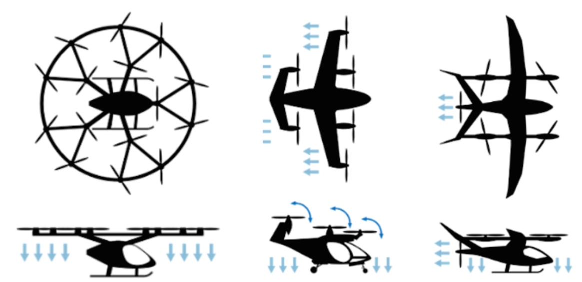

Fig.1 Classification of eVTOL aircraft

1 Evtol Aircraft

According to Vertical Flight Society[1], the eVTOL aircraft may be classified into five categories according to their flight patterns: Wingless (multicopter), vectored thrust, lift & cruise, hover bikes/personal flying devices and electric rotorcraft. The rotor is angled to generate not only lift for vertical flight but also thrust for forward flight. The wing is adopted to fly efficiently at high speed and long range.

In this paper, three categories were investigated. The multicopter type is equipped with multiple rotors without wing, and flight speed and direction are controlled by changing the angle of the rotor axis of rotation for both vertical and horizontal flight. The lift & cruise type generates lift to counteract gravity in the vertical direction from the fixed rotor during takeoff, landing, and hovering, while propulsion in the forward direction is generated by the propeller and lift is generated by the wings during cruise, separately. The vectored thrust type uses couples of tilt-rotor to transit lift in vertical flight and thrust in forward flight by changing the axis of rotation of the rotor. The multicopter type is designed for low-speed and very short range flight, while the vectored thrust and lift & cruise types combine designs of helicopter for vertical flight and the fixed-wing aircraft for horizontal cruising.

2 Flight Mission

Like conventional helicopter, the flight profile of the eVTOL aircraft may be split into several phases as shown in Fig.2. The main operational profile can be generally divided into six phases: ① Takeoff and vertical climb, ② climb and forward flight, ③ cruise at specified altitude, ④ descent and forward flight, ⑤ vertical descent and landing, and ⑥ hovering. Results of the aircraft performance, which are calculated using published and assumed data, are estimated for each flight phase. Any civil transport aircraft must meet specified airworthiness regulations with regard to flying qualities and performance. The eVTOL aircraft must also satisfy operational requirements such as flight altitude, speed, range, payload, etc.

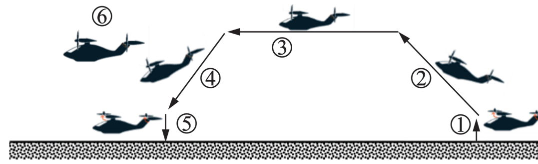

Fig.2 Main mission flight profile

3 Electric Propulsion System

A basic configuration of the electrically-powered propulsion system is shown in Fig.3. Propeller or rotor is driven by the electric motor. Blades are rotated at high speed, accelerating the air that passes through it, and gains propulsive force from the reaction. Electricity is supplied by the power source, such as battery equipped with battery management system (BMS). The electric propulsion system basically consists of a motor, inverter, thermal management system, and transmission. The speed and torque are transmitted to the propeller to generate thrust. The inverter converts the direct current from the rechargeable battery or electric power generator to the alternating current output of the motor drive, and controls the motor speed so that the output torque reaches the required value. In the case of a high-speed propeller, the motor may directly drive the propeller. For a low-speed rotating helicopter rotor, the rotor must be rotated through a reduction gear.

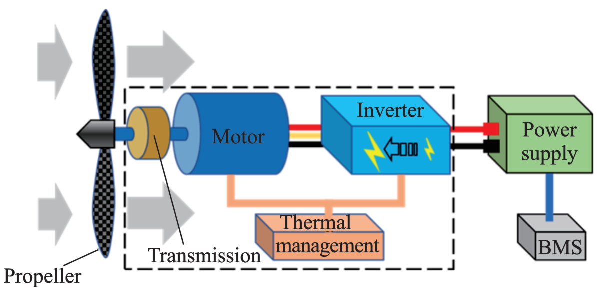

Fig.3 Rotor system of electric propulsion

4 Synthesis Process of Flight Performance Estimation

Unlike conventional helicopters and fixed-wing aircrafts, the eVTOL aircraft usually adopts rotors, propellers and fixed wings. A lot of formulae of aircraft theories of statistical data are often used in conceptual and preliminary designs of these aircrafts. In order to provide overall flight performance of the eVTOL aircraft, a synthesis process was proposed to analyze complex configurations including rotor, propeller, fixed wing, and other components of airframe. The synthesis process is shown in Fig.4.

Due to the complexity of eVTOL aircraft, considerable knowledge is required to conduct performance estimation and design of the eVTOL aircraft. On the other hand, most of the eVTOL aircraft are not detailly published yet, and geometries and specification are almost not available correctly. In this

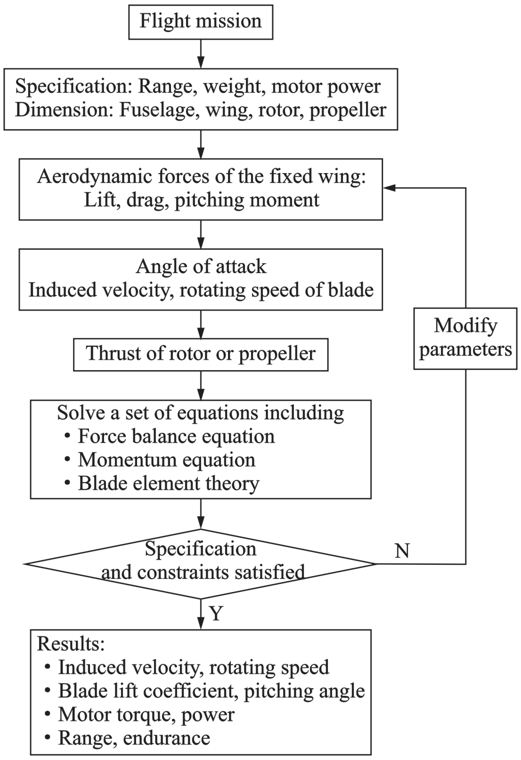

Fig.4 Synthesis process of performance estimation

study, to provide reliable estimation, all data of the eVTOL aircrafts were collected from various materials published by aircraft makers, graphs, news, articles, web resource and so on. Data were finally adjusted for overall consistency.

The computational results were validated by using published data of the existing helicopters[6], and then applied to several eVTOL aircrafts to estimate their flight performance at hovering, climb and descent, and forward flight.

5 Aerodynamic Theories of Evtol Aircraft

The flight performance was estimated for hovering, climb and descent, and forward flight based on theories of the rotorcraft[7] and fixed-wing aircraft[8]. Fig.5 shows aerodynamic models for the momentum analysis of the rotor and propeller during forward flight. Airflow is accelerated by the rotating disk and the thrust is generated when air passes through blades. Airflow is accelerated by the rotating disk, which is inclined in the forward direction, and the thrust T is generated when the air passes through the rotor blades. Therefore, the rotor surface must be tilted forward at an angle of attack α

relative to the flow in the flight direction. The induced velocity by rotating blades may be calculated according to the momentum conservation law. According to the momentum conservation law, the thrust generated by the rotor is equal to the product of the air mass flow rate through the rotating disk and the induced velocity. Details may be referred in Ref.[6].

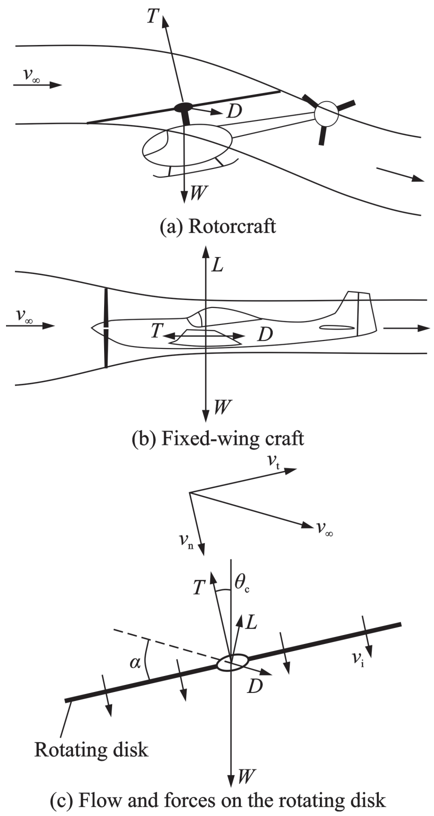

Fig.5 Aerodynamic models of aircraft

Fig.5 shows the airflow passing through the rotating disk and the equilibrium of forces. W is the weight of the vehicle, L the rotor lift, D the aerodynamic drag, v_n and v_t are the components of flight V in the normal and tangent directions, respectively. The speed v_i is the induced velocity by the rotor blades and may be calculated according to the momentum conservation law, and v_∞ the air velocity relative to the aircraft in the forward direction. Since the thrust T generated by the rotor is equal to the product of the air mass flow rate through the rotating disk and the increase of flow velocity, it can be calculated using Eq.(1). Here, ρ is the air density and S the area of the rotating disk.

$$T=2\rho S v_i\sqrt{v_\infty^2+2v_\infty v_i\sin\alpha+v_i^2} \tag{1}$$

It can be seen from Fig.5 that conditions for in-flight equilibrium of forces are

$$\begin{cases} L=W\cos(\alpha-\theta_c)-T\cos\alpha \\ D=T\sin\alpha-W\sin(\alpha-\theta_c) \end{cases} \tag{2}$$

In forward flight, the airspeed ratios are defined by Eqs.(3) and (4), and the induced ratio is given in Eq.(5).

$$\mu_n=\frac{v_n}{\Omega R}=\frac{v\sin\alpha}{\Omega R} \tag{3}$$

$$\mu_\tau=\frac{v_t}{\Omega R}=\frac{v_\infty\cos\alpha}{\Omega R} \tag{4}$$

$$\lambda_i=\frac{v_i}{\Omega R} \tag{5}$$

where Ω is the rotor rotation speed and R the radius of the rotor rotating surface.

The inflow ratio is defined as

$$\lambda=\frac{v_n}{\Omega R}+\frac{v_i}{\Omega R}=\mu_n+\lambda_i \tag{6}$$

The thrust coefficient is defined by

$$C_T=\frac{T}{\rho S v_{tip}^2} \tag{7}$$

where v_{tip} is the blade tip speed. Then, a general form for the inflow ratio may be written as

$$\lambda=\mu_n+\frac{C_T}{2\sqrt{\mu_t^2+\lambda^2}} \tag{8}$$

From these equations, the thrust of the aircraft, the induced velocity, and the rotor rotation speed can be calculated. For the hovering flight, the induced velocity v_i was defined as

$$v_i=v_h=\sqrt{\frac{T}{2\rho S}} \tag{9}$$

For an aircraft, the total power required at the rotor or propeller can be expressed by

$$P=P_p+P_i+P_0+P_c \tag{10}$$

The parasite power required to overcome the air drag of aircraft is estimated by the aerodynamic theory of the aircraft.

$$P_p=Dv_\infty=\frac{1}{2}\rho v_\infty^3 S_w C_D \tag{11}$$

where S_w is the referred area, and C_D the drag coefficient of the airframe. The induced power P_i required for the rotor was calculated from the induced velocity v_i. The factor k was set to 1.15 according to experiments in order to account for a multitude of aerodynamic phenomena.

$$P_i = kTv_i \tag{12}$$

The profile power P_0 is then the energy per unit time consumed to overcome the air drag of the rotor blades, and is defined by Eq.(13) based on the blade element momentum theory.

$$P_0 = \frac{1}{8}\rho N_b S v_{tip}^3 \sigma\left(1 + K\mu^2\right) C_{d0} \tag{13}$$

where N_b is the number of blades, σ the stiffness value of the rotor rotating surface calculated from the blade geometry, and C_{d0} the average drag coefficient of the blades section, which was estimated in this study. K is the value to calculate the three-dimensional effects on the drag, and the airspeed rate μ is zero during hovering flight.

P_c is the climb power required to increase the gravitational potential of the aircraft, and v_c is the climb velocity, so we have

$$P_c = Wv_c \tag{14}$$

For the eVTOL aircraft, the input power of the motor system is then calculated by

$$P_{motor} = \frac{P}{\eta_m \eta_d} \tag{15}$$

where η_m and η_d are efficiencies of motor and driving system, respectively. These formulae can be applied to both of rotor and propeller.

6 Results of Flight Performance

In this study, 12 eVTOL airplanes were investigated as shown in Fig.6, and three of them were typically picked up, based on the data available in the middle of 2023. Red data were estimated.

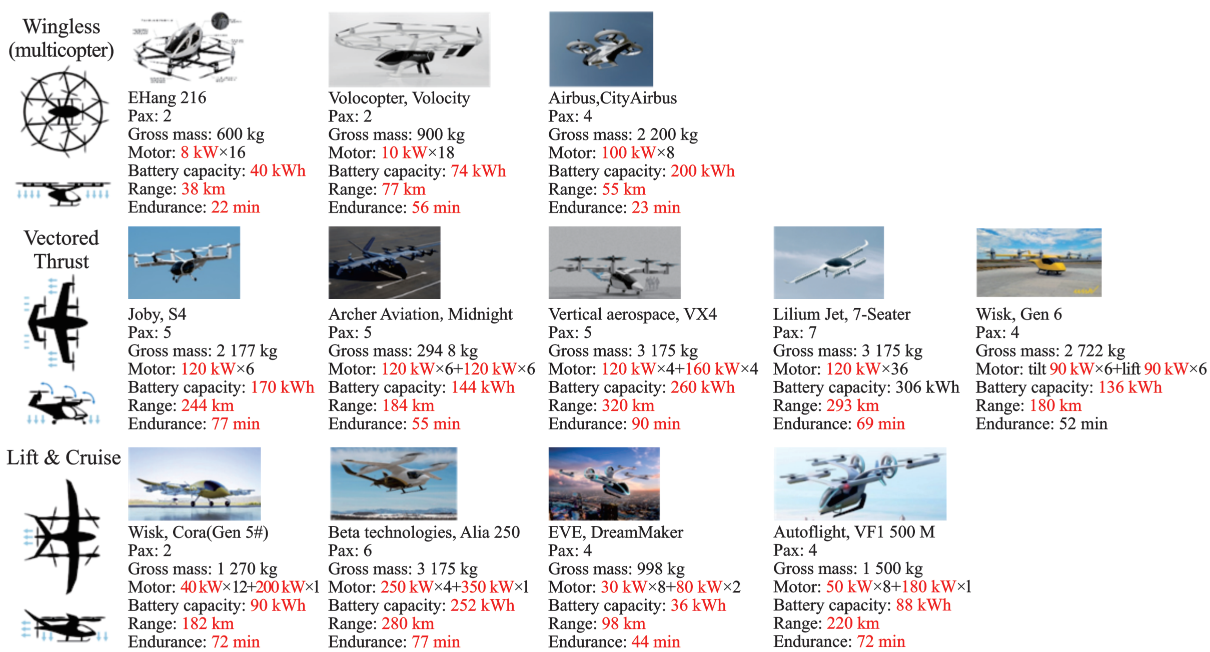

Fig.6 Summary of flight performance estimated (red data were estimated by the author)

6.1 Overall flight performance

Flight performance of the 12 eVTOL aircraft as shown in Fig.6 are compared. The power required for each aircraft in hovering flight were calculated as shown in Fig.7(a). Because volocity and DreamMaker have lighter weights and lower disc loadings, the total required powers are significantly lower than those of other eVTOL aircraft. According to Eq.(9), volocity has a large rotating area and results in a lower disc loading and thus a small induced velocity in hovering. The vectored thrust type has a higher weight and resulting in a higher disc loading than those of multicopter type. Fig.7(b) shows comparison of the power to weight ratio, i.e., the efficiency of propulsion supplied by the power system at cruising flight. The lower the power to weight ratio, the lower the power is required. It is found that the Multicopter type is not effective. On the other hand, because the wing was aerodynamically efficient than rotor, both the Vectored Thrust type and Lift & Cruise type consumed much lower power as compared with the Multicopter type. Fig.7(c) shows the cruising rate, i.e. range to energy ratio, which is the efficiency of energy at cruising flight. It is found that for the same energy carried in the aircraft, the Multicopter type has a shorter range, the Vectored Thrust type is better, and the Lift & Cruise type can significantly increase the range. Generally, the Lift & Cruise type has the best performance at cruising. As an exception, Lilium Jet (number 7 in Fig.7), which adopted 36 ducted fans for propulsion, has bad performance not only at hovering but also at cruising, and especially at hovering. Obviously, Lilium Jet is more suitable for short but not vertical takeoff and landing.

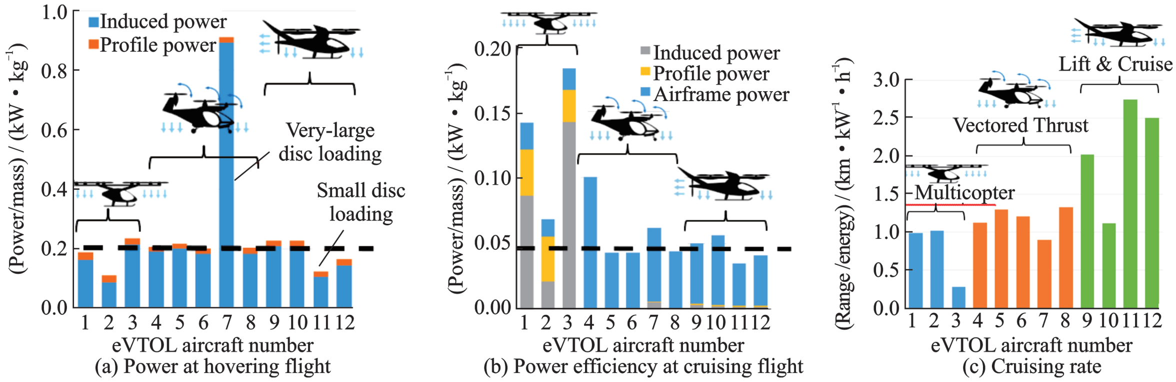

Fig.7 Flight performance of 12 eVTOL aircrafts

6.2 Motor performance

According to the results of performance estimation, it was found that the adopted motor system should be determined by the eVTOL configuration and flight conditions. Most eVTOL aircraft are designed using multiple rotors, and each motor has an output power less than 100 kW as shown in Fig.6.

Typical examples of flight profiles of motor output are compared in Fig.8. It was found that each eVTOL aircraft has large changes in output of pow-

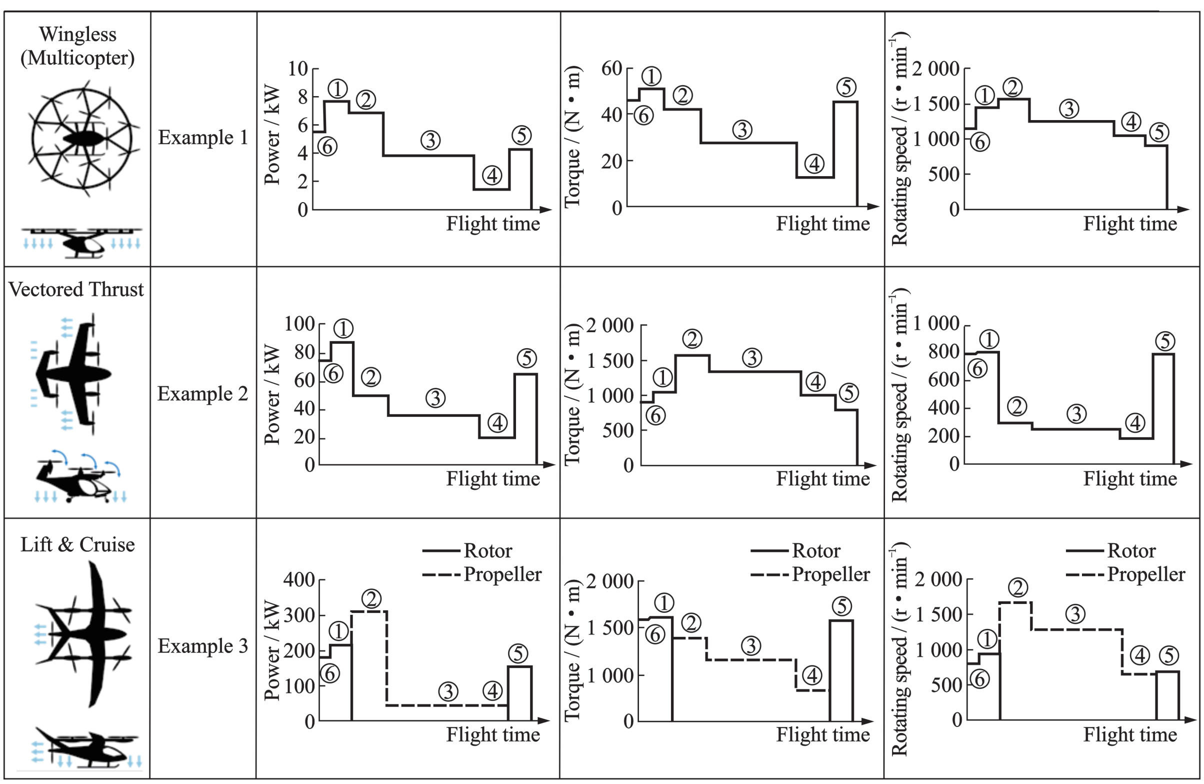

Fig.8 Examples of flight profile of motor output

er, torque, and rotating speed at different phases. The propeller's rotational speed varies within a certain range, and the torque varies widely. In contrast, the rotating speed of the tilt rotor changes in a large range and the torque keeps large. The characteristics of the two are very different in flight performance. A representative efficiency map of motor was shown in Fig.9. It can be seen that the motor efficiency does not change significantly when the propeller is driven, while the efficiency of the tilt rotor decreases at low rotational speeds in level flight. Motor design is required to avoid a decrease in motor efficiency when the tilt rotor rotates at low speeds, since it accounts for a large proportion of the energy consumed during cruise flight.

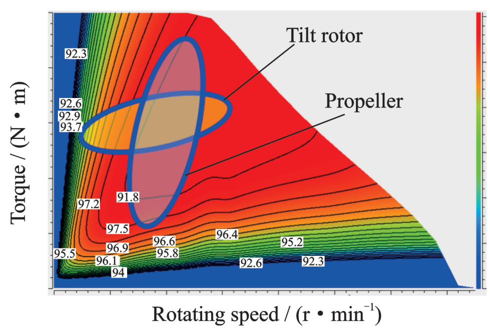

Fig.9 Representative efficiency map of motor

7 Conclusions

The theory of rotorcraft aerodynamics was extended and combined with the theory of fixed wing in order to calculate aerodynamic performance of rotor, propeller and tiltrotor. A synthesis process was then developed to estimate flight performance for various types of eVTOL aircrafts.

By the proposed method, flight performance of 12 eVTOL aircraft were investigated. Some suggestions for eVTOL design and operation were obtained as following.

(1) Multicopter eVTOL aircraft are suitable for short range with low speed.

(2) The vectored thrust eVTOL aircraft and lift & cruise eVTOL aircraft are more efficient for longer range with high speed.

(3) Different types of eVTOL aircraft should match different motors. Motor design is required to consider its performance at different flight phases.

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Competing interests The author declares no competing interests.

(Production Editor: ZHANG Huangqun)

利用旋翼机和固定翼飞机的空气动力学理论综合估算电动垂直起降飞行器的飞行性能

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摘要: 根据旋翼机和固定翼飞机的气动理论开发了一个综合方法过程用于估算电动垂直起降(Electric vertical takeoff and landing, eVTOL)飞行器的飞行性能。这种飞机通常采用多旋翼垂直飞行,螺旋桨和机翼的不同组合方式实现飞行。其中,对旋翼和螺旋桨的气动性能采用传统动量理论分析和旋翼元素分析。本文利用此综合理论研究了12架eVTOL飞行器的飞行性能,包括多旋翼飞行器、矢量推进飞行器和升力巡航飞行器。计算了悬停、爬升和下降以及巡航水平飞行,不同飞行状态时驱动电机、旋翼和机身的飞行特性。据此,可以进一步确定电力推进系统的性能指标,以匹配螺旋桨或旋翼,从而满足飞行任务。

关键词: 电动垂直起降飞行器;先进空中飞行器;旋翼;固定翼;飞行性能;气动理论