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ESTIMATION OF EVTOL FLIGHT PERFORMANCE USING ROTORCRAFT THEORY

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Abstract

The purpose of this study was to investigate representative eVTOL aircraft, which have been actively researched and developed around the world in recent years. Aerodynamics theories of rotorcraft and fixed-wing aircraft were applied to estimate power required and rotating speed of rotor and propeller, cruise speed, lift to drag ratio, and so on. A computational tool has been developed to calculate flight performance of various types of eVTOL aircraft. Several eVTOL aircrafts have been investigated. As representative, three different eVTOL aircrafts were compared their flight performance in each phase of the flight mission profile, such as hovering, climb and cruise. It is concluded that the multicopter eVTOL aircraft is suitable to the flight of short range with low speed. The vectored thrust eVTOL aircraft and lift & cruise eVTOL aircraft is more efficient for longer range with high speed.

Keywords: eVTOL, Rotorcraft Theory, Flight Performance

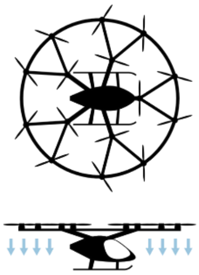
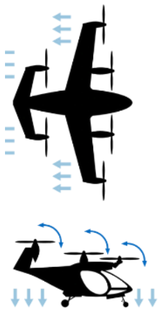
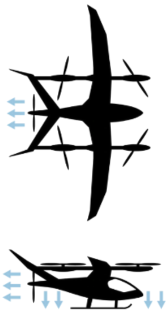
1. Introduction

With development of battery, electric propulsion, light material and control technologies, there has been significant increase in research of the eVTOL (electric vertical takeoff and landing) aircraft in recent years. The eVTOL aircraft is characterized by the use of multiple electric-powered rotors or fans for lift and propulsion, along with fly-by-wire systems for control, and moves people with zero emission and low noise by air in urban districts. It is considered to use as air taxi in order to improve the traffic condition and satisfy the growing need for new vehicles for urban air mobility (UAM).

The eVTOL aircraft are attracting attention as a near future means of transportation in the near ground space, which is different from land transportation such as road car and railway train. Related research and development is being widely conducted around the world. Compared to conventional airplanes and helicopters, the eVTOL aircraft have many advantages in terms of cost and environment. It is expected to have economic effects such as avoiding traffic jam, improving convenience in remote islands and mountainous areas, and being used for disaster relief and logistics. The eVTOL aircraft are classified into three types for civil aviation, multicopter type, lift & cruise type, and vectored thrust type. Table 1 shows the classification of eVTOL aircraft and their specification.

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. 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 short range flight, while the vectored thrust and lift & cruise types combine the design of helicopter for vertical flight and fixed-wing aircraft for horizontal cruising. All 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.

Table 1. Classification of eVTOL aircraft

Category	Wingless (Multicopter)	Vectored Thrust	Lift & Cruise
Maker, Name	Volocopter, Volocity	Joby, S4	Beta Technologies, Alia 250
photo			
feature	 18 fixed rotor	 6 tilt-rotor, wing	 4 fixed rotor, 1 propeller, wing
Gross weight [lb]	1984	4800	7000
PX	2	5	6
Empty weight [lb]	1543	1724	2631
Rotor diameter [ft]	7.5	9.5	13
propeller diameter [ft]	-	-	8
Wing area [ft^2]	-	170	250

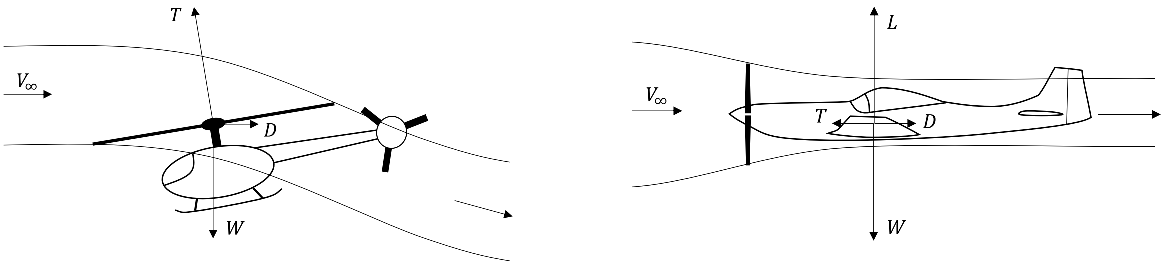
The purpose of this study is to investigate performance of different eVTOL aircrafts, which including hovering, climb and descent, and forward flights, and provide technical information for operational feasibility. The method is based on theories of rotorcraft and fixed-wing aircraft that are modified to be used for the eVTOL aircraft. As representatives of eVTOL aircrafts, Volocopter's Volocity [1], the Joby's S4 [2] and Beta Technologies' Alia 250[3] are analyzed according to information available by the authors.

2. Methods of Flight Performance Estimation

In this study, a computational tool was developed using the theory of rotorcraft aerodynamics [4]. In this study, the computational results was validated by using published data of the existing helicopters, and then extended to eVTOL aircrafts. The flight performance was estimated for hovering, climb and descent, and forward flight based on theories of the rotorcraft[4] [5] and fixed wing[6] .

2.1 Basic Theory

Figure 2 shows aerodynamic models for the momentum analysis of the rotor and propeller during forward flight. Figure 3 shows airflow passes the rotation disk and forces act on the disk. 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 direction opposite to the direction of travel.



(a) rotorcraft (b) fixed-wing craft

Figure 2 Aerodynamic models of aircraft

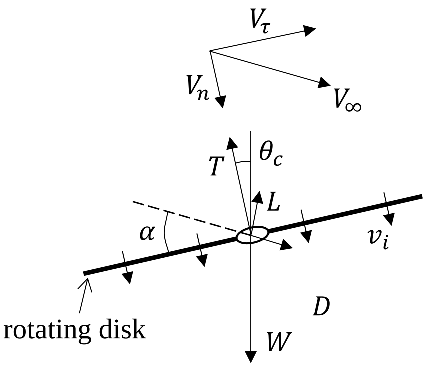


Figure 3 Flow and forces on the rotating disk

As shown in Figure 2, the airflow passes through the rotating disk and the equilibrium of forces. The speed v_i is the induced velocity by the rotor blades and may be calculated according to the momentum conservation law, and V_∞ is 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 equation (1). Here, ρ is the air density $[\mathrm{kg/m^3}]$ and S is the area of the rotating disk $[\mathrm{m^2}]$.

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

It can be seen from Figure 3 that a condition for in-flight equilibrium is

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

In forward flight, the airspeed ratio is defined by Equation (3) and (4), and the induced ratio is Equation (5), where Ω is the rotor rotation speed and R is the radius of the rotor rotating surface.

$$\mu_n = \frac{V_n}{\Omega R} = \frac{V\sin\alpha}{\Omega R} \tag{3}$$

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

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

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 Equation (7).

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

Then, a general form for the inflow ratio may be written as

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

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

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

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

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

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

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

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.

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

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 Equation (13) based on the blade element momentum theory. N_b is the number of blades, σ is the stiffness value of the rotor rotating surface calculated from the blade geometry, C_{d0} is the average drag coefficient of the blades section, which was estimated in this study. The airspeed rate μ is zero during hovering flight.

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

P_c is the climb power required to increase the gravitational potential of the aircraft. V_c is the climb velocity.

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

For the eVTOL aircraft, the input power of the motor system is then calculated using Equation (15).

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

The power consumption the motor, E_h[kWh], is calculated as the product of the calculated motor power requirement and the flight time t.

$$E_h = P_{motor} \times t_h \tag{16}$$

These equations can be generally applied to both rotor and propeller, and also used for the tiltrotor which generates lift and propulsion.

The cruise time t_f was then calculated from the total required power by using Equation(17).

$$t_f = \frac{\zeta E_{bat} - E_{hov} - E_{cruise} - E_{climb} - E_{descent}}{P_{motor}} \tag{17}$$

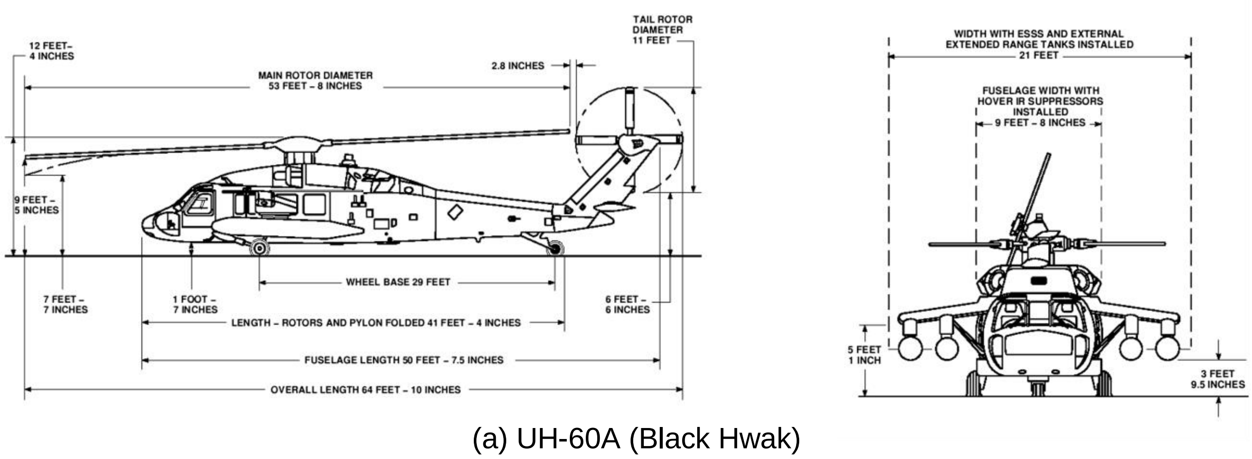
where E_{bat}[kWh] is the battery capacity, which is calculated as the product of the battery energy density ρ_E[Wh/kg] and the battery weight. For the sake of safety, a part of electric energy must be reserved. In this paper, the electric consumption is limited to a maximum of 85% of the battery capacity.

The cruise distance R_{cruise} is obtained by the product of the cruise time and the cruise speed V_{cruise}, and the cruising performance of the aircraft can be estimated.

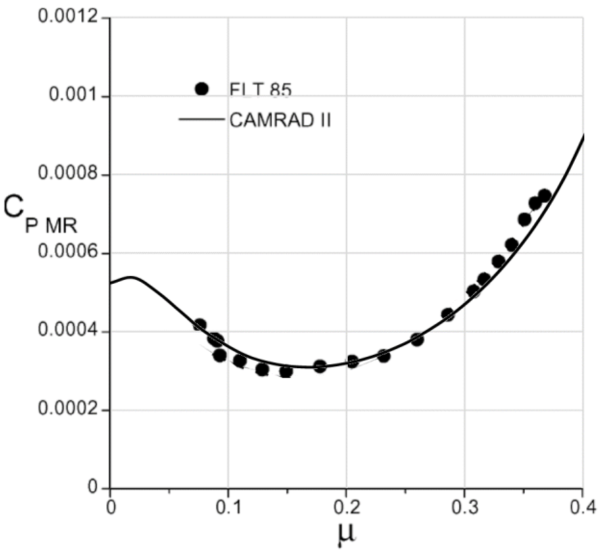
$$R_{cruise} = V_{cruise} t_f \tag{18}$$

2.2 Validation

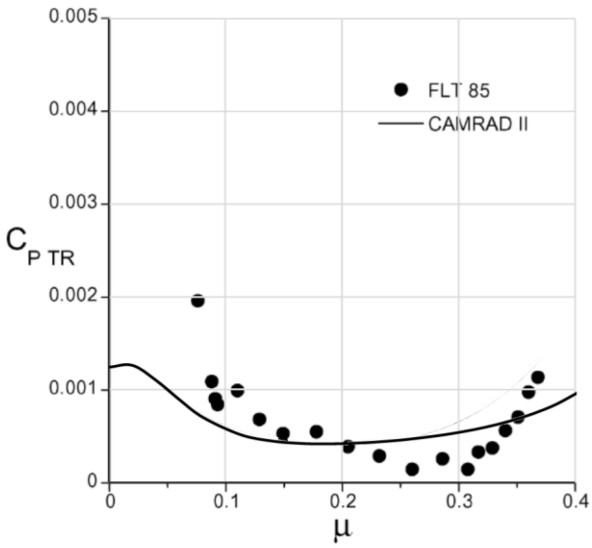
The method is validated by the flight test data of UH-60A helicopter[7] . The predicted power coefficients of the main and tail rotors are compared and agreed well with the flight data.



(a) UH-60A (Black Hwak)



(a) main rotor



(b) tail rotor

Figure 4 Validation of the prediction and flight test data of UH-60A helicopter at weight coefficients C_W = 0.0065.

3. Estimation Results

Like conventional helicopter, the flight profile of the eVTOL aircraft may be split into several phases as shown in Figure 5. The main operational profile can be generally considered in the following segments:

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
⑥ Hovering

Results of the aircraft performance, which are calculated using published and assumed data, are obtained for each flight phase.

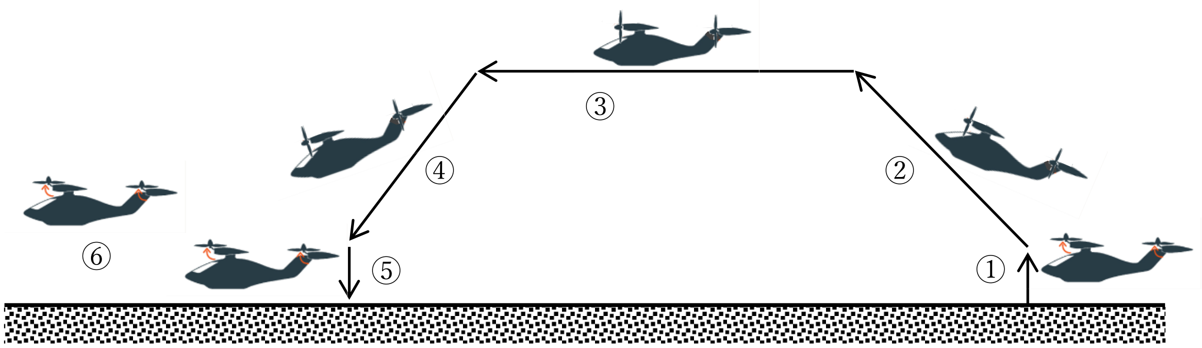


Figure 5. Main mission flight profile

3.1 Hovering Flight

The power required for each aircraft in hovering flight were calculated as shown in Table 2. Because Volocity is much lighter than S4 and Alia 250, the total power required is significantly lower. According to Equation (9), Volocity has a large rotating area and results a lower disk loading and thus a small induced velocity in hovering. Table 2 shows that the Multicopter type has a larger rotor diameter, resulting in a larger rotating surface area and lower disk loading. The Vectored Thrust type has a higher weight than the Multicopter type, resulting in a higher disk loading.

Table 2: Calculated and assumed data of the eVTOL aircrafts in hovering

	Volocity	S4	Alia 250
Altitude [ft]	Sealevel	Sealevel	Sealevel
Blade mean lift coefficient [-] (assumed)	0.35	0.65	0.7
Total power required [kW]	116	451	724
Rotating speed of rotor [rpm]	1325	800	800
Induced velocity [m/s]	7.0	14.8	16.1
Tip speed of blade [m/s]	159	122	138
Disk loading [kg/m^2]	12.2	55.0	64.4
solidity [-]	0.066	0.27	0.16

3.2 Vertical Climb

The performance are compared with each other in the phase of vertical climb. Effect of ground is not considered in the calculation. Due to power available of motor system, the rate of climb is assumed to be different values. The power required, rotating speed of blade and tip speed of blade of Volocity are increased significantly as compared with those of S4 and Alia 250. The reason is that Volocity adopted a fixed-pitch rotor that the efficient becomes lower with the increase of the disk inflow, while S4 and Alia 250 are thought to adopt variable-pitch rotor and can get high performance.

Table 3: Calculated of the eVTOL aircrafts at vertical climb

	Volocity	S4	Alia 250
Altitude [ft]	150	150	150
Rate of climb [m/s]	2.5	5.0	5.0
Total power required [kW]	150	500	863
Rotating speed of rotor [rpm]	1553	809	930
Induced velocity [m/s]	7.0	15	16.0
Tip speed of blade [m/s]	186	123	214

3.3 Climb and Forward Flight

It was assumed that S4 and Alia 250 fly at constant speeds during aircraft climbs to cruise altitude from the end of vertical climb in this study. The rate of climb is specified to a value according the power required and conventional aircraft. Here, S4 and Alia 250 were calculated at averaged altitudes in the phase of climb and forward flight, but Volocity is not discussed. The cruise altitudes are specified according to the published data. S4 combines capabilities of the vertical flight and horizontal flight by 6 tilt-rotors which are angled in different phases. The rotors are progressively tilted forward when the eVTOL aircraft transits from vertical to forward flight. In contrast, Alia 250 adopts 4 fixed rotors for vertical flight and 1 propeller for forward flight, separately. In this study, it is assumed that Alia 250 is driven by the propeller, and lift is generated by the fixed wing, while the rotors are stopped during climb and forward flight. Calculated data are summarized in Table 4. Both of S4 and Alia 250 generate lift by the fixed wings, so the power required is largely reduced as compared with that in hovering and vertical climb. So the rotating speed, induced velocity and tip speed of blade are also significantly reduced in this phase.

Table 4: Calculated data of the eVTOL aircrafts at climb and forward flight

	S4	Alia 250
Altitude [ft]	150~4500	150~8000
Rate of climb [ft/min]	720	720
Horizontal speed [mph]	160	160
Total power required [kW]	200	296
Rotating speed of rotor or propeller [rpm]	295	1640
Induced velocity [m/s]	0.47	4.3
Tip speed of blade [m/s]	45	209
L/D	14.3	18.3

3.4 Cruise

The power required for level flight is a function of flight speed. Results are given in Figure 6 for the three eVTOL aircrafts investigated in this paper. It is observed that at low flight speed, the power required decreases with increasing flight speed, but increases again as the flight speed increases further. It is apparent that the maximum range flight, where P/V is a minimum, is normally specified as the cruise condition, and the cruise speed is obtained when a line drawn from the origin of the axes is tangent to the power-speed curve. It results different cruise speeds for the different aircrafts. On the other hand, the maximum endurance is obtained at the condition that the power required is the minimum. The cruise speed of Volocity is significantly lower than those of S4 and Alia 250.

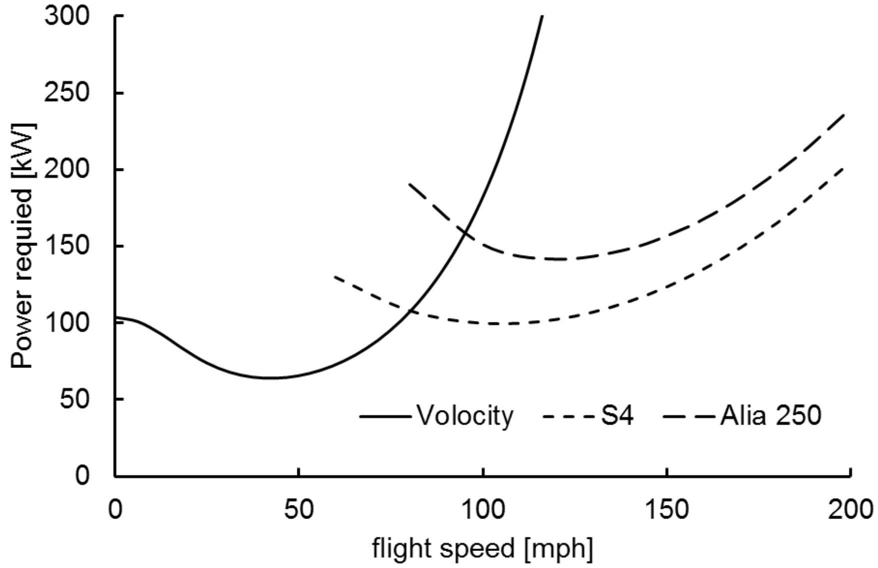


Figure 5. Predictions of power required in level flight

According to the results of power-speed curves in Figure 5, the cruise speed are determined for each eVTOL. Performance are summarized in Table 5. It is found that different aircraft has quite different performance. Compared with propeller-driven Alia 250, the tiltrotor-driven S4 has much more lower rotating speed and tip speed of blade mostly due to the configuration with distributed rotors, and may be expected a lower noise flight.

Table 5: Calculated data of the eVTOL aircrafts at cruise

	Volocity	S4	Alia 250
Altitude [ft]	1500	4500	8000
Cruise speed [mph]	56	140	160
Total power required [kW]	91	114	168
Rotating speed of rotor or propeller [rpm]	1478	225	1255
Induced velocity [m/s]	1.98	0.28	2.6
Tip speed of blade [m/s]	177	34	160
L/D	-	14.3	18.3

4. Conclusion

In this study, the performance of different eVTOL aircrafts were estimated and compared. The theory of rotorcraft aerodynamics was extended to calculate rotor, propeller and tiltrotor, and a computational tool was developed to estimate various type of eVTOL aircrafts. Three representatives of eVTOL aircrafts were analyzed in each flight phase, including hovering, climb, cruise, descent.

To reduce energy consumption, a larger rotor diameter and lower disk loading is required for the multicopter type in hovering flight. It is concluded that the multicopter eVTOL aircraft is suitable to the flight of short range with low speed. The vectored thrust eVTOL aircraft and lift & cruise eVTOL aircraft is more efficient for longer range with high speed.

Further development is being carried out for conceptual design of new eVTOL aircrafts. A design tool will be used for not only calculation of flight performance, but also prediction of technology feasibility, selection of mission determination, and trial calculation of operating costs.

5. Copyright Statement

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