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Aerodynamics Theories for Estimating Flight Profile of eVTOL Aircraft

Prof. Zhong Lei

Suwa University of Science, Japan

Contact: lei@rs.sus.ac.jp

Original Papers:

1. Yuto Fukumine, Zhong Lei, : "Estimation of eVTOL Performance Using Rotorcraft Theory", the 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 2022.9
2. Haruki Takizawa, Zhong Lei: "Operational Feasibility Study of Air Taxi Service using eVTOL in Japan" the 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 2022.9

Outline of content

- Research Objectives and Approach
- eVTOL Airplane of UAM
- Synthesis of Propeller and Rotor Theories
- Results and Discussions
- Conclusion

Research Objective

Objectives

- ✓ to investigate flight performance of representative eVTOL aircrafts, which including hovering, climb and descent, and forward flights,
- ✓ to provide technical information for aircraft design and operational feasibility.

The method is based on theories of rotorcraft and fixed-wing aircraft that are modified to be used for the eVTOL aircraft.

It is expected that this tool may be used for design and operation of eVTOL aircrafts.

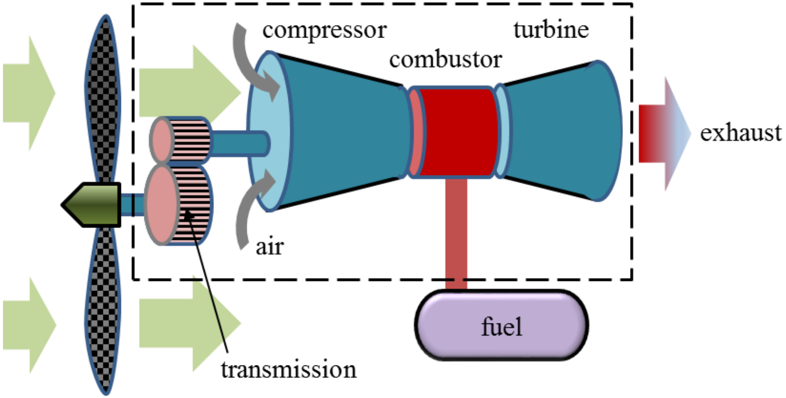


Fig. Turboprop propulsion

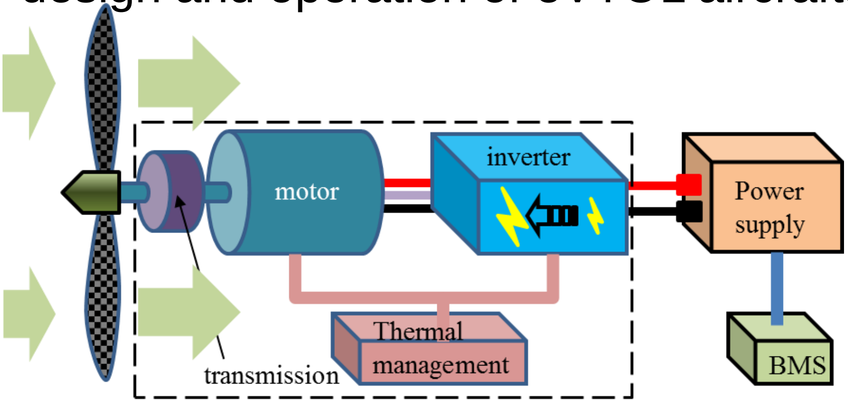


Fig. Electric propulsion

Research Approach

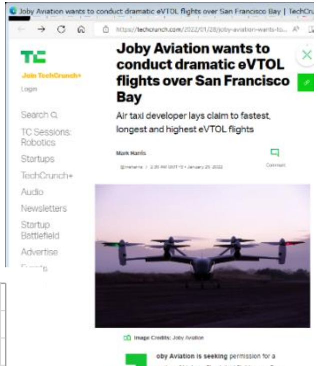
- Information of eVTOL aircraft are very limited.
- A synthesis of rotary blade theory was developed to estimate flight performance using statistical data, empirical rules, aircraft engineering theory.
- Calculations were adjusted for overall consistency.

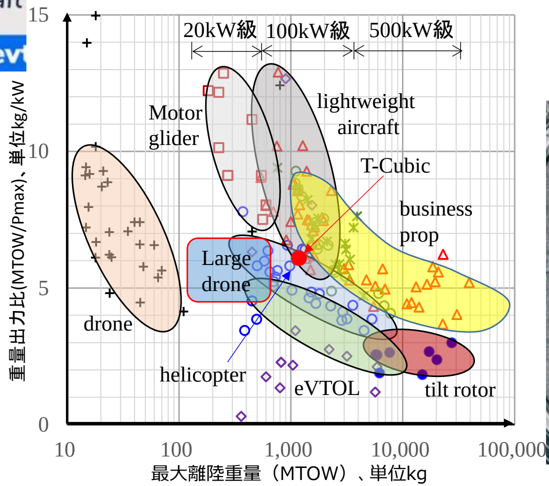
Aircraft data collection
- Data published by aircraft maker
- Data read from published graph
- New, articles, web resource and so on

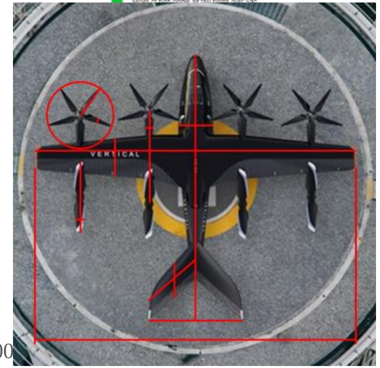
Parameter determination：
- Database of existing aircraft
- Statistical and empirical formula
- overall consistency with published data

Performance evaluation：
- fixed-wing and helicopter engineering theory
- Constraints of shape, performance
- Satisfaction of published specifications

Results







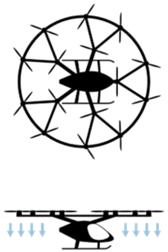
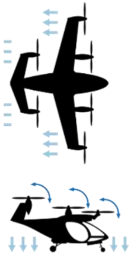
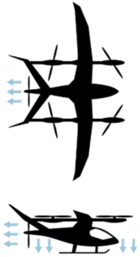
Characteristics of eVTOL Aircraft

Multicopter type:
- coupled rotors, no wing
- flight speed direction are controlled by changing the angle of the rotor axis of rotation

Vectored thrust type:
- coupled tilt-rotors, wing
- transit lift in vertical flight and thrust in forward flight by changing the axis of rotation of the rotor.

Lift & cruise type:
- coupled fixed-rotors and wing
- generates lift on the fixed rotor
- generates thrust in forward direction by the propeller
- generates lift on the wing during cruise

Table. eVTOL aircraft investigated in this study

Category	Wingless (Multicopter)	Vectored Thrust	Lift & Cruise
Maker, Name	Volocopter, Volocity	Joby Aviation, 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

Flight Mission

Like conventional helicopter, the flight profile of eVTOL aircraft may be divided into several phases.

Mission Includes altitude, flight time, range, speed.

- **Take-off**: Climb vertically at hover power(no horizontal movement)
- **Climb**: Climb to cruise altitude
- **Cruise**: Flight phase that occurs when the aircraft levels after a climb to a cruise altitude and before it begins to descend
- **Descent**: Aircraft begins approach to final landing. Has both horizontal and vertical component
- **Landing**: Vertical landing at hover power (no horizontal movement)
- **Hovering**: Stay in the air by rotor

① Takeoff and vertical flight

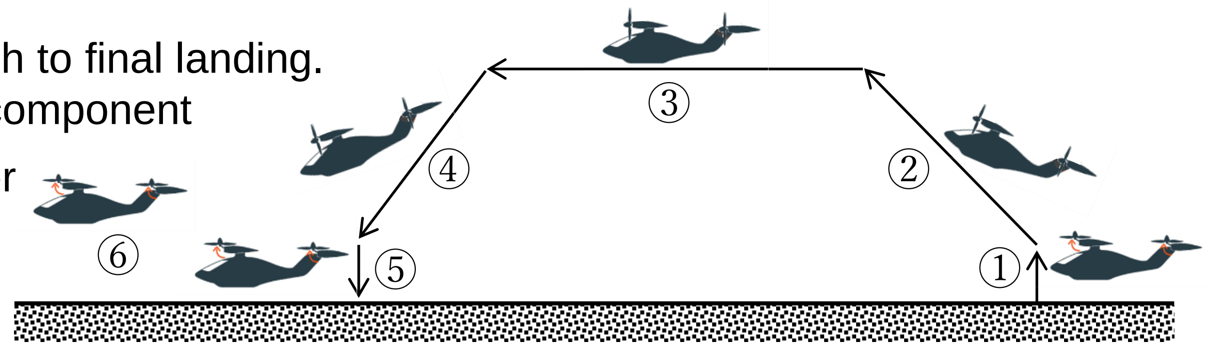
② Climb and forward flight

③ Cruise at specified altitude

④ Descent and forward flight

⑤ Vertical descent and landing

⑥ Hovering



Main mission flight profile

Synthesis of Propeller and Rotor Theories: Fixed-Wing Aircraft

Induced velocity $w = 2v_i$ Advance ratio $J = \dfrac{V}{\Omega R}$ $\Omega = 2\pi n$

According to Bernoulli's principle

$$\Delta p = H_1 - H = \left[p + \frac{1}{2}\rho(V+w)^2\right] - \left[p + \frac{1}{2}\rho V^2\right] = \rho\left(V + \frac{1}{2}w\right)w = 2\rho(V+v_i)v_i$$

Thrust generated by propeller is calculated by momentum equation

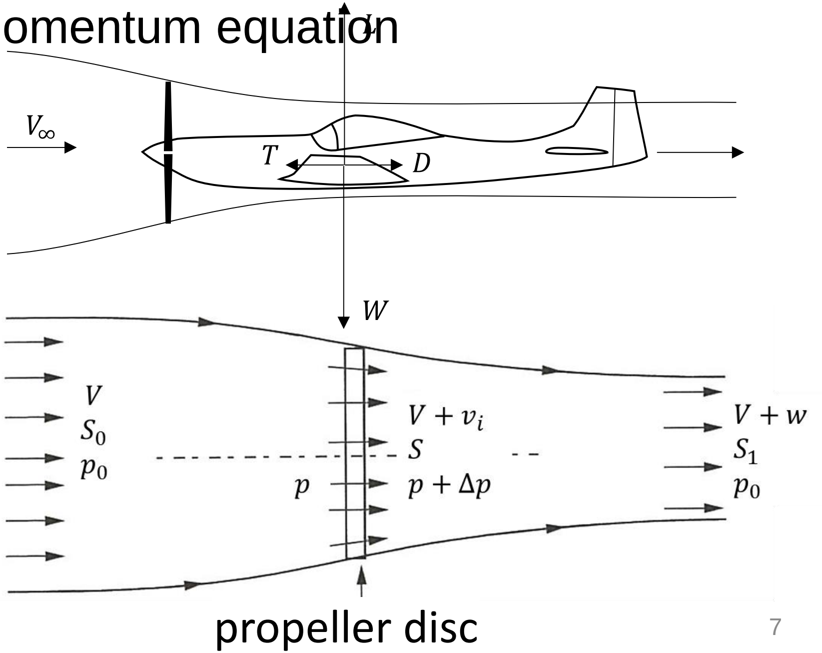
$$T = \Delta p S = \rho S(V+v_i)w = 2\rho S(V+v_i)v_i$$

Then, induced velocity may be solved

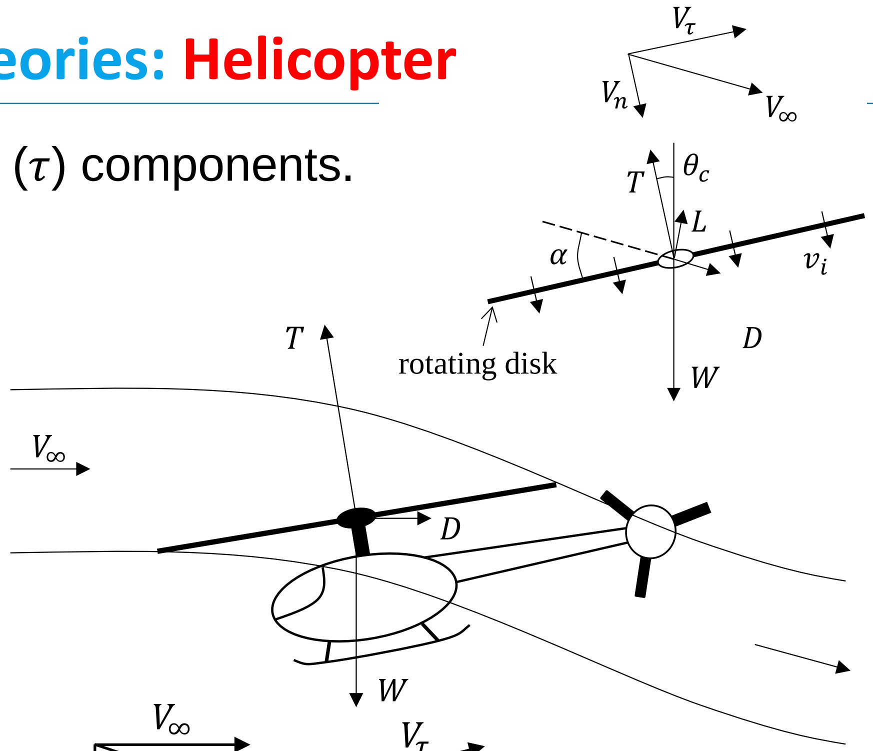
$$\frac{v_i}{v_s} = -\frac{V}{2v_s} + \sqrt{\left(\frac{V}{2v_s}\right)^2 + 1}$$

At static condition（$V = 0$）

$$v_s = \sqrt{\frac{T}{2\rho S}}$$



Synthesis of Propeller and Rotor Theories: Helicopter



Break velocity into normal (n) and tangential (τ) components.

Tip speed ratio

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

Inflow ratio

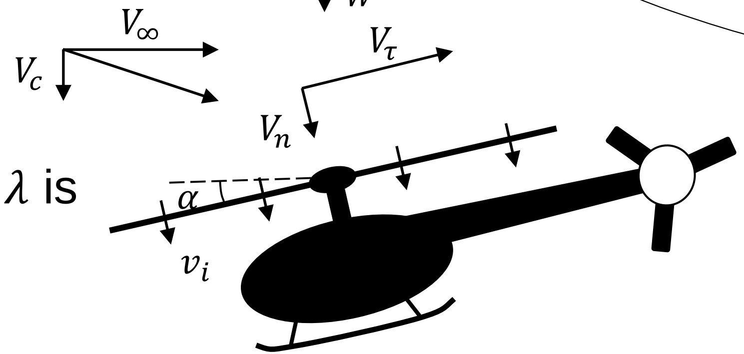
$$\lambda = \frac{V_n}{\Omega R} + \frac{v_i}{\Omega R} = \mu_n + \lambda_i$$

Induced velocity at hovering

$$v_h = \sqrt{\frac{T}{2\rho\pi R^2}} \quad \text{and} \quad \lambda_h = \sqrt{\frac{C_T}{2}}$$

Induced velocity at forward flight

$$v_i = \frac{v_h^2}{\sqrt{(V_\tau)^2 + (V_n + v_i)^2}} = \frac{v_h^2}{U}$$

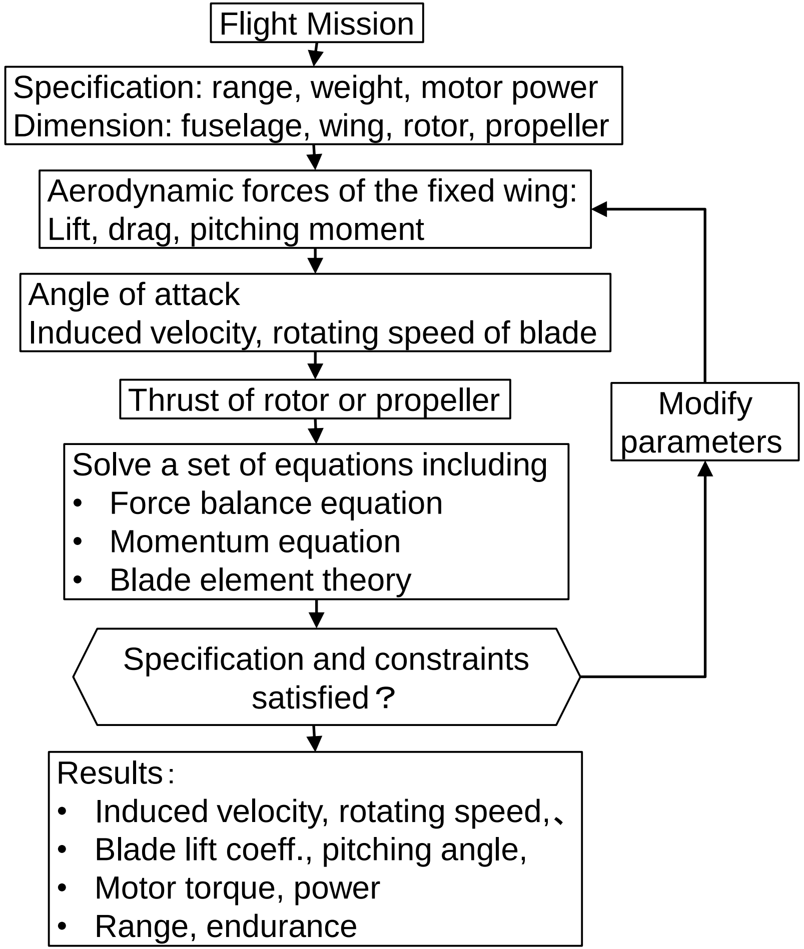


Substitute into the equation for the inflow ratio λ is

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

Solved by iteration

Flight Performance Estimation Using the Synthesis Theory



Force balance $L = W\cos\theta_{FP}$, $T = D + W\sin\theta_{FP}$

Momentum equation $T = 2\rho A v_i\sqrt{V_\infty^2 + 2V_\infty v_i \sin\alpha + v_i^2}$

Equation of inflow ratio $\lambda = \mu_n + \dfrac{C_T}{2\sqrt{\mu_\tau^2 + \lambda^2}}$

Relation of thrust coefficient and lift coeff. $C_T = \dfrac{1}{6}\sigma\bar{C}_L$

Total power required $P = P_i + P_0 + P_p + P_c$

① induced power $P_i = T \times v_i$

② Profile power

$$P_0 = \frac{1}{8}\rho N_b c R(\Omega R)^3(1 + K\mu^2)C_{d0} = \frac{1}{8}\rho A V_{tip}^3\sigma(1 + K\mu^2)C_{d0}$$

③ Airframe parasite power

$$P_p = D \times V_\infty = \frac{1}{2}\rho V_\infty^2 S C_{Df} \times V_\infty = \frac{1}{2}\rho V_\infty^3 S C_{Df}$$

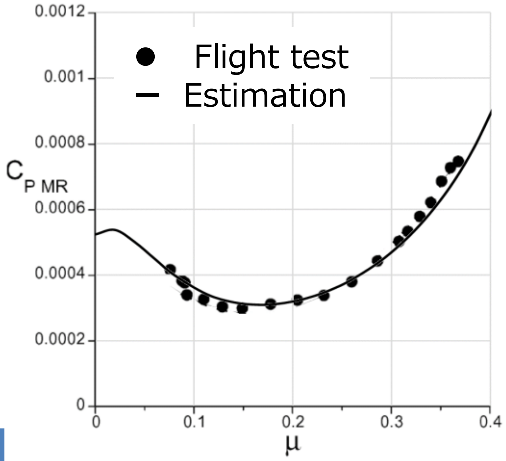
④ climb power

$$P_c = W \times V_c$$

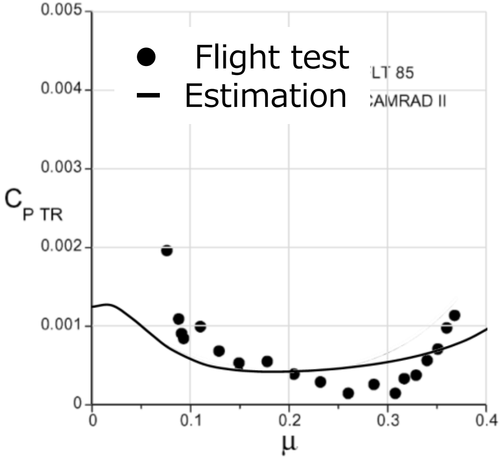
Validation : Performance Estimation of UH-60A (Black Hwak)

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

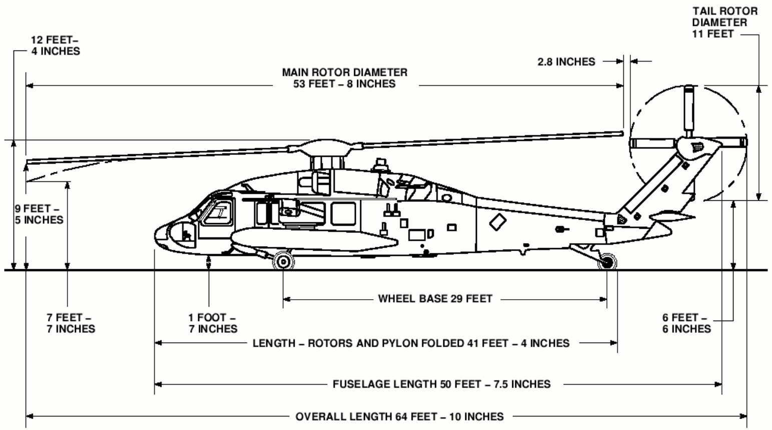
	Main rotor	Tail rotor
airfoil	SC1095/ SC1094	SC1095
radius [m]	8.18	1.68
chord length [m]	0.527	0.250
number of blades	4	4
rotating speed at hovering [rpm]	258	1190



main rotor

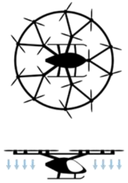
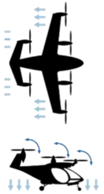
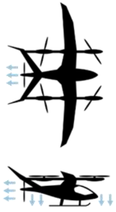


tail rotor

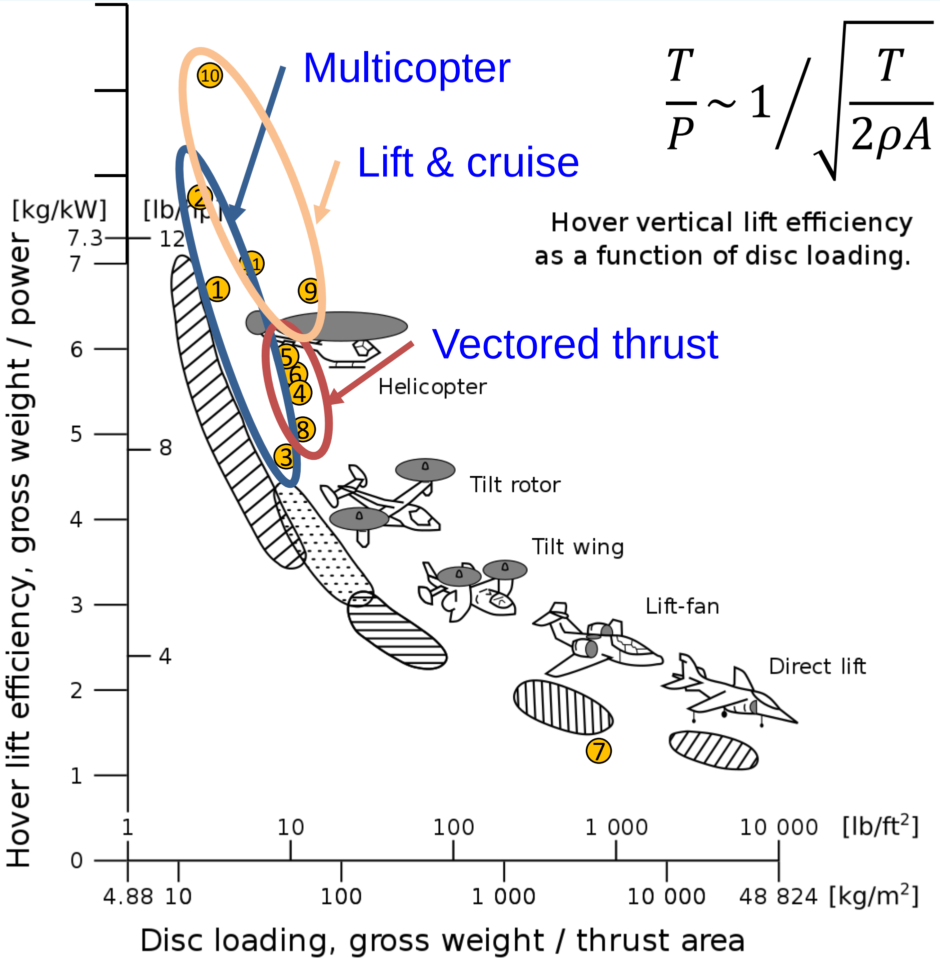


Investigation of Flight Performance of eVTOL Airplanes

11 eVTOL airplanes were investigated, 3 of them were typically picked up, based on the data available in the middle of 2022. Red data are estimated.

Wingless (Multicopter) 	 EHang 216 Pax：2人 Gross weight：600kg Motor：8kWx16 Battery capacity：40kWh Range：15km Endurance：20min	 Volocopter, Volocity Pax：2人 Gross weight ：900kg Motor ：8kWx18 Battery capacity ：74kWh Range ：48km Endurance ：45min	 Airbus, CityAirbus Pax ： 4人 Gross weight ：2200kg Motor ：100kWx8 Battery capacity ：200kWh Range ：53km Endurance ：23min	
Vectored Thrust 	 Joby, S4 Pax ： 5人 Gross weight ：2177kg Motor ：120kWx6 Battery capacity ：166kWh Range ：236km Endurance ：69min	 Archer Aviation, Maker（100%） Pax ： 5人 Gross weight ：3175kg Motor ：90kWx3+120kWx3 Battery capacity ：258kWh Range ：287km Endurance ：90min	 Vertical Aerospace, VX4 Pax ： 5人 Gross weight ：3175kg Motor ：120kWx4+160kWx4 Battery capacity ：260kWh Range ：340km Endurance ：90min	 Lilium Jet, 7-Seater Pax ： 7人 Gross weight ：3175kg Motor ：120kWx36 Battery capacity ：306kWh Range ：293km Endurance ：69min
Lift & Cruise 	 Wisk, Cora (Gen 5#) Pax ：2人 Gross weight ：1270kg Motor ：40kWx12+200kWx1 Battery capacity ：88kWh Range ：182km Endurance ：72min	 Beta Technologies, Alia 250 Pax ：6人 Gross weight ：3175kg Motor ：250kWx4+350kWx1 Battery capacity ：544kWh Range ：267km Endurance ：71min	 EVE, DreamMaker Pax ：4人 Gross weight ：998kg Motor ：30kWx8+80kWx2 Battery capacity ：36kWh Range ：116km Endurance ：53min	 Autoflight, VF1500M Pax ：4人 Gross weight ：1500kg Motor ：50kWx8+180kWx1 Battery capacity ：88kWh Range ：252km Endurance ：80min

Disc Loading and Weight-to-Power Ratio



Characteristics

Multicopter type:

- Large disc area
- Low disc loading

Vectored thrust type:

- All aircrafts has similar performance, except Lilium Jet

Lift & cruise type:

- High efficiency
- Rotor for hovering
- Propeller for wing-borne flight

Generally, it is recommended that the weight-to-power ratio

- be larger than 5 kg/kW at hovering
- be larger than 20 kg/kW at cruising

Overall Performance (based on the data available in the middle of 2022)

- Lift & Cruise type has the best performance at cruising.
- #7, Lilium Jet has bad performance, especially at hovering.

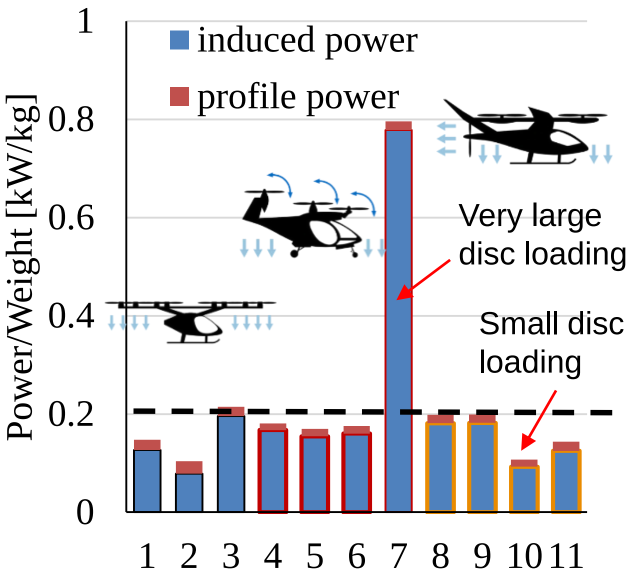


Fig. Power at hovering flight

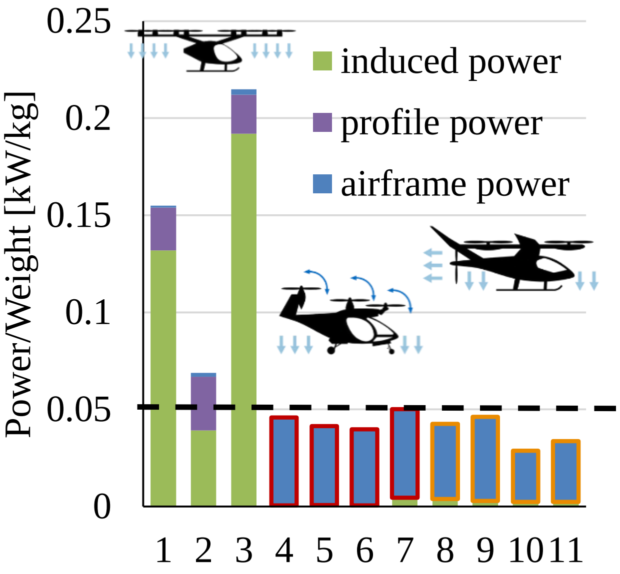


Fig. Power at cruising flight

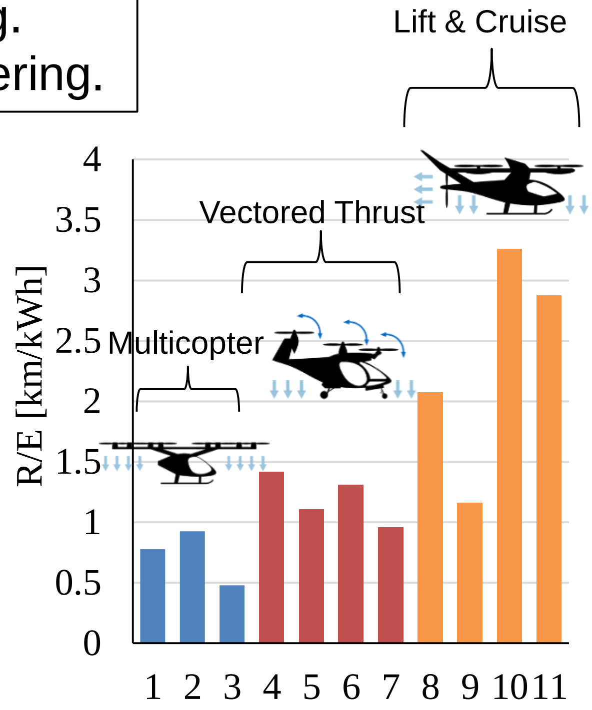


Fig. Cruising rate

Cruising rate $r = R_{\text{total}}/E_{\text{total}}$ Multicopter < Vectored Thrust < Lift & Cruise

Where, R_{total} : range, E_{total} : consumed energy

Results and Discussions: Hovering

- Power is increased as the weight at hovering.
- Power-to-weight ratio is increased with disk loading.

A large rotating area results in a lower disk loading, thus a benefit of power-to-weight ratio.

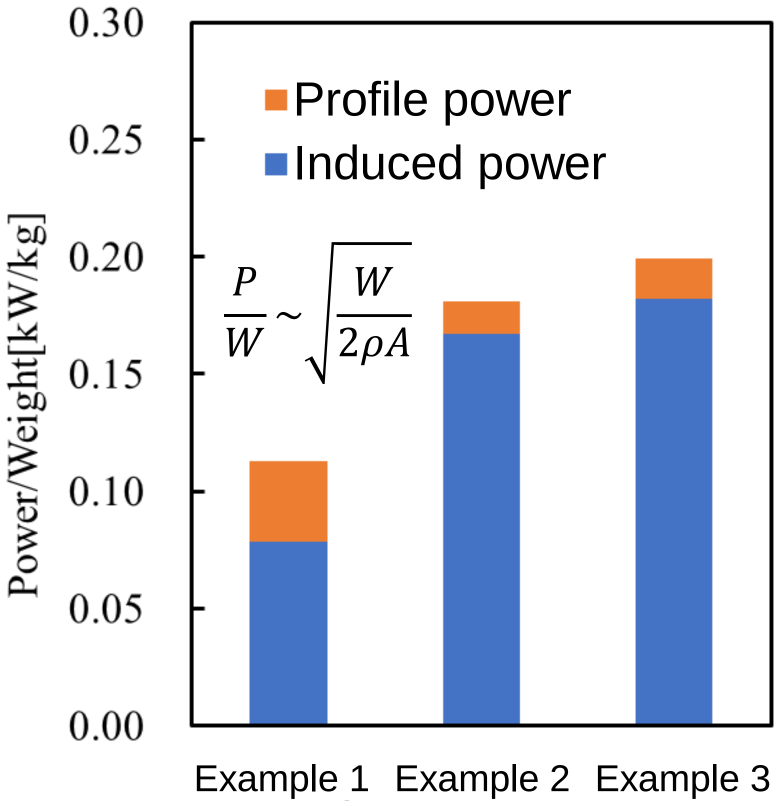


Fig. Power breakdown at hovering

Results and Discussions: Climb and Descent

At vertical climb and descent, total power consumption is decreased with increase of climb and descent rate, respectively.

Suitable rate of climb and descent should be selected to reduce power consumption.

Generally, the rate is recommended to be larger than 4 m/s.

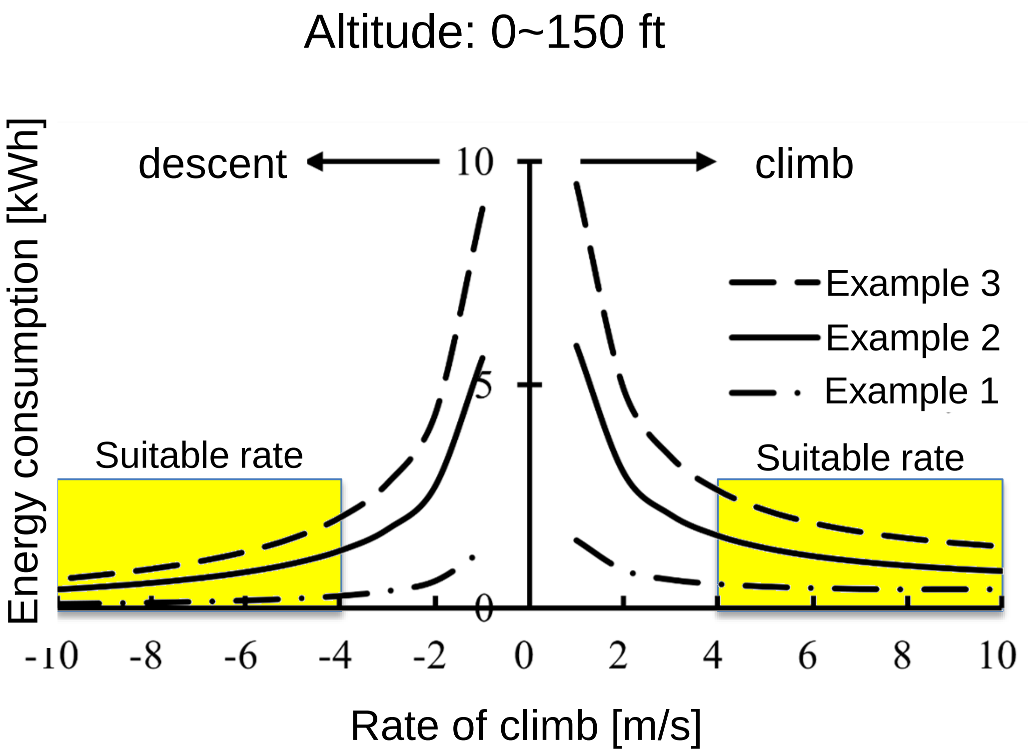


Fig. Estimation results of total power consumption

Results and Discussions: Performance at Cruising

- Multicopter Volocity is suitable for short range.

- The wing has significant effects on the cruise speed and necessary power at cruising.

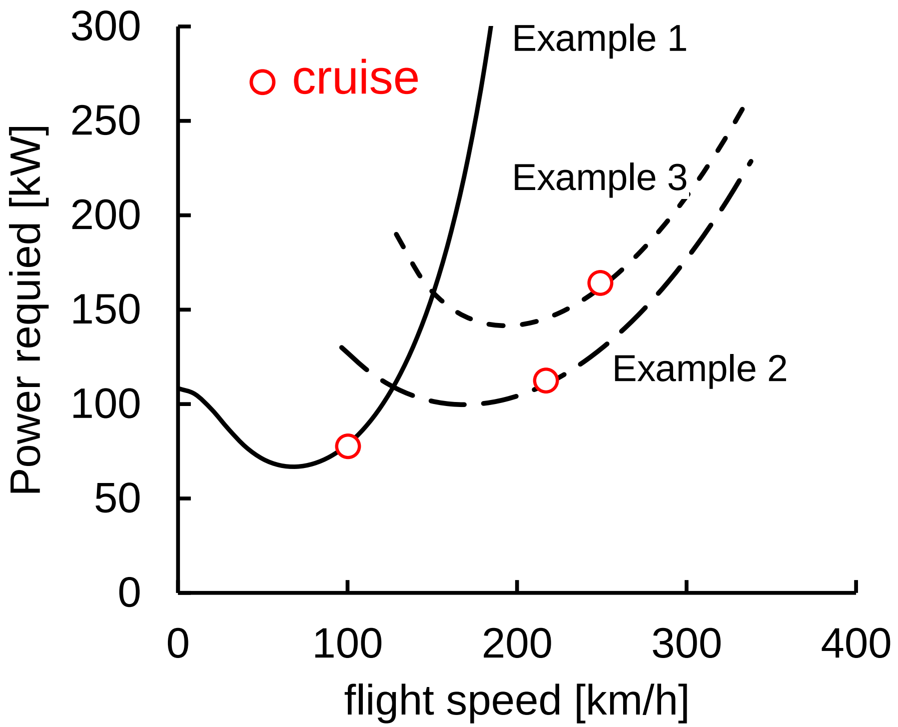
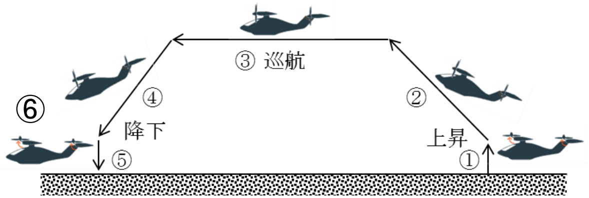


Fig. Power required in level flight

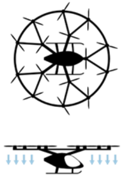
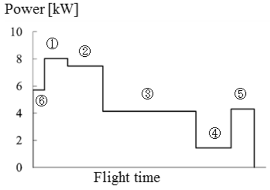
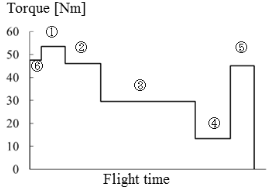
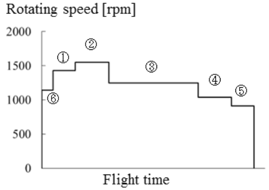
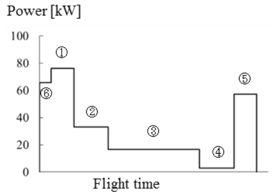
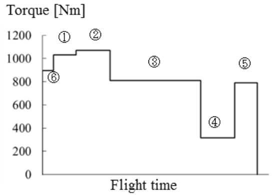
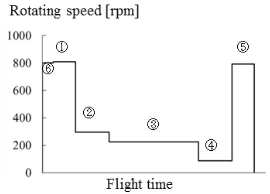
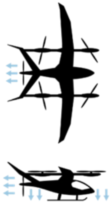
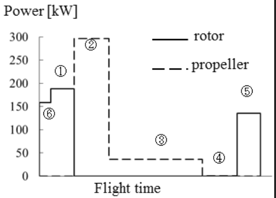
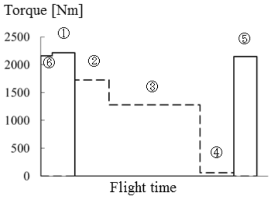
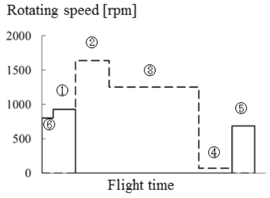
Results and Discussions: Flight Profile of Motor Output

- Different characteristics for fixed-pitch / variable-pitch blade, fixed / tilt rotor, rotor / propeller
- Large changes in output of power, torque, and rotating speed at different phases

It suggests that different type should match different motor.



Flight phases

		Power	Torque	Rotating speed
Wingless (Multicopter) 	Example 1			
Vectored Thrust 	Example 2			
Lift & Cruise 	Example 3			

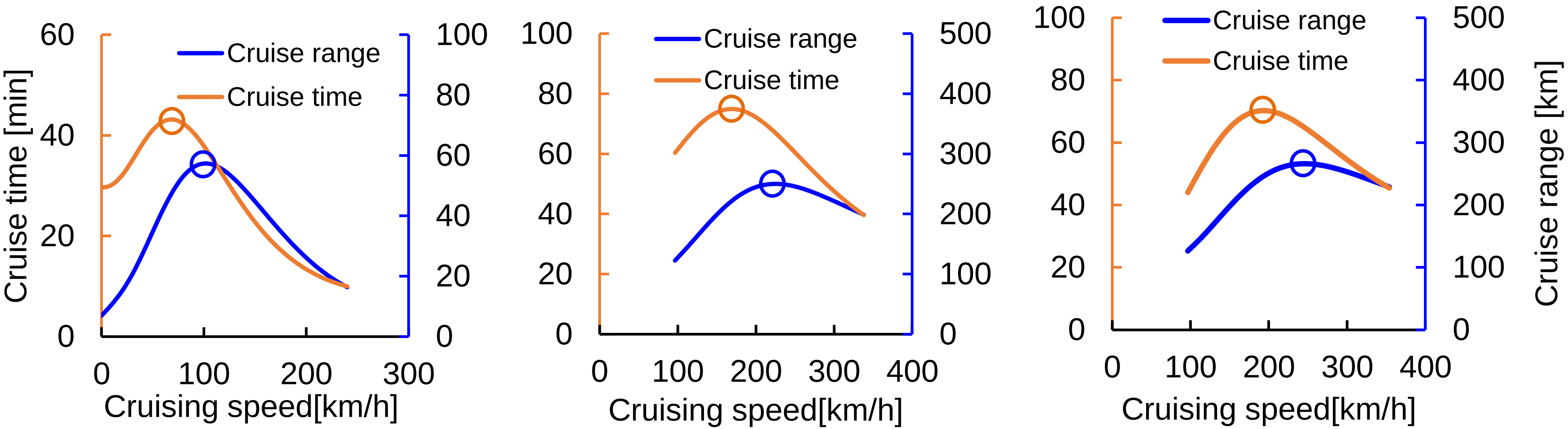
Results and Discussions: Range and Endurance

Factors which most influence range and endurance, include

- **flight profile** : altitude, hovering time, climb rate, cruise speed
- **aerodynamics** : rotor, propeller and airframe
- **propulsion** : efficiency, energy density, battery capacity (especially for eVTOL)

Both lift & cruise type (b) and vectored thrust type (c) may fly more than 1 hour and 150 miles.

It is suggested that both of them may be used as UAM.



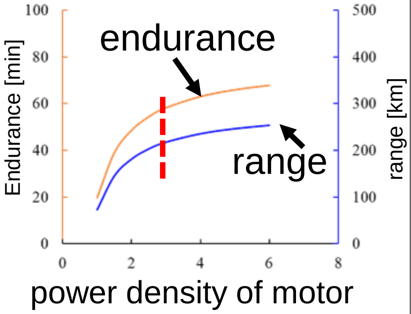
(a) Example 1 (multicopter) (b) Example 2 (vectored thrust) (c) Example 3 (lift & cruise))

Results and Discussions: Power Density of Motor

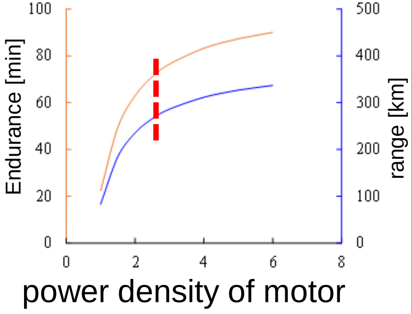
With consideration of cost and performance, power density of motor 3~4kW/kg is suitable for eVTOL airplane.

Vectored Thrust

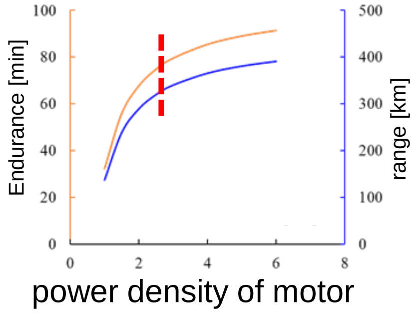
Example



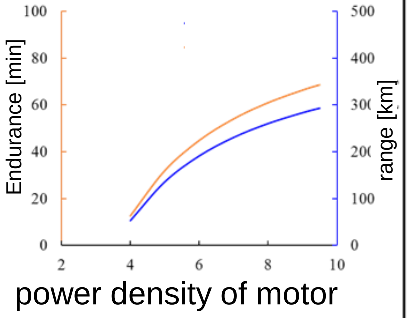
Example



Example

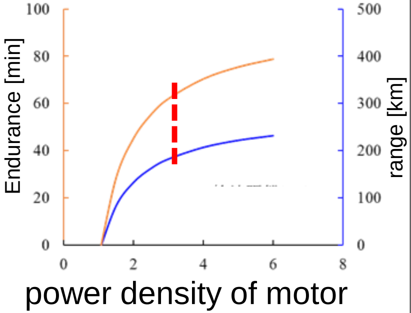


Example

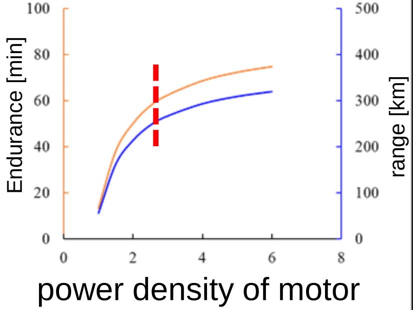


Lift & Cruise

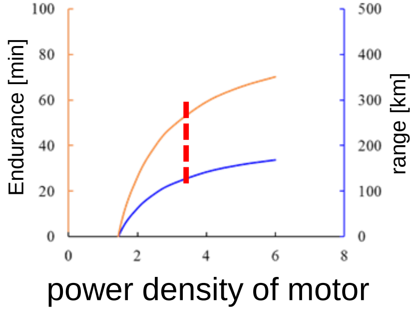
Example



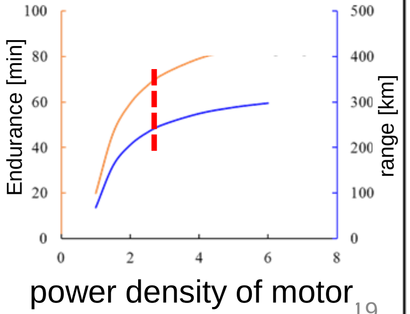
Example



Example

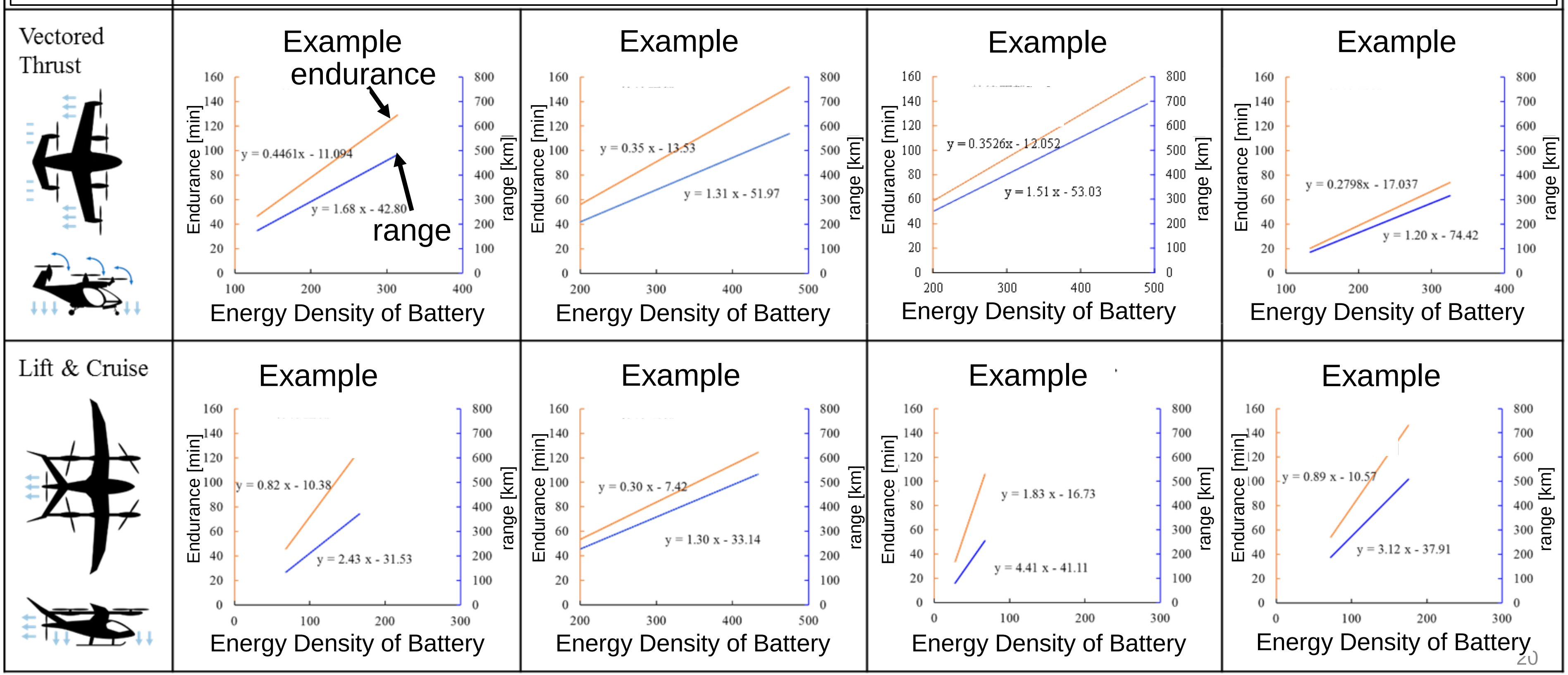


Example



Results and Discussions: Energy Density of Battery

Energy density of battery may be determined to match specified range and endurance with consideration of cost and performance.



Conclusion

The theory of rotorcraft aerodynamics was extended to calculate rotor, propeller and tiltrotor, and a computational tool was developed to estimate various types of eVTOL aircrafts.

Some suggestions for eVTOL design and operation.

- Generally, it is recommended that the ratio of weight-to-power should be larger than 5 kg/kW at hovering, be larger than 20 kg/kW at cruising.
- Suitable rates of climb and descent should be selected to reduce power consumption. Generally, the rate is recommended to be larger than 4 m/s.
- Energy density of motor 3~4 kW/kg is suitable for eVTOL airplane.
- Energy density of battery should be larger than 200Wh/kg, which is dependent on the eVTOL aircraft.
- It suggests that different type of eVTOL aircraft should match different motor.
- Multicopter eVTOL aircraft is suitable for short range with low speed.
- The vectored thrust eVTOL aircraft and lift & cruise eVTOL aircraft are more efficient for longer range with high speed.

Hope this computation tool may be used to help design and operation of eVTOL aircraft.

Thanks for your attention