PERFORMANCE OF A DUAL-CONTROLLED ROTOR IN LEVEL FLIGHT

Yuto Sayama, y-sayama@st.go.tuat.ac.jp, Tokyo University of Agriculture and Technology (Japan)
Kaito Hayami, k-hayami@st.go.tuat.ac.jp, Tokyo University of Agriculture and Technology (Japan)
Yasutada Tanabe, tan@chofu.jaxa.jp, Japan Aerospace Exploration Agency (Japan)
Hideaki Sugawara, sugawara.hideaki@jaxa.jp, Japan Aerospace Exploration Agency (Japan)
Masaharu Kameda, kame@cc.tuat.ac.jp, Tokyo University of Agriculture and Technology (Japan)

Abstract

Feasibility of a "level flight" multi-rotor aircraft, a concept for a high-speed multi-rotor aircraft characterized by a horizontal attitude during forward flight, using a separately placed propeller for propulsion is investigated. The performance of a single rotor used in this aircraft at forward flight is evaluated through numerical simulations. Also, a dual-controlled rotor whose control parameters are rotational speed and blade pitch angle was investigated. The numerical results show that the effective lift-to-drag ratio of the horizontal rotor is higher than that of the forward-tilted rotor. Adding control of the blade pitch angle improves the effective lift-to-drag ratio compared to rotors that can only be controlled by rotation speed. The optimal value of the effective drag is determined by the relationship between the power and the drag. The rotational speed changes the rotor power, and the drag reduction depends on the blade pitch angle. In addition, the untwisted blade shows a higher effective lift-to-drag ratio than the twisted blade. The blade twist significantly affects the drag of the rotor.

1. BACKGROUND

Multi-rotor aircraft are being developed for the transportation of people and cargo. Airbus Helicopters has proposed and is developing multi-rotor urban air mobility called CityAirbus.[1] The National Aeronautics and Space Administration (NASA) has also proposed a multi-rotor urban air mobility aircraft.[2]

The improvement in the flight speed of multi-rotor aircraft enables them to reach their destinations faster and thus provides more efficient transportation. It is needed to study the feasibility of high-speed multirotor type aircraft. Elytron Aircraft has proposed a small tiltrotor aircraft that uses a fixed box wing configuration.[3-4] The fixed-wing aircraft has a higher forward flight performance than conventional rotorcraft, but the mechanism of rotor tilting causes complexity and increase in the size of the aircraft. If the forward flight performance of the rotorcraft can be equivalent to that of a fixed-wing aircraft, the fixed-wing will be unnecessary, and a higher performance VTOL can be developed.

Research on high-speed helicopters is in progress, and a new type of helicopter called a compound helicopter has been proposed, and the high-speed flight has been demonstrated. Eurocopter developed the X3 demonstrator, where record-breaking high-speed flight was demonstrated.[5] X3 was constructed with a single main rotor, lateral propellers, and a fixed wing. Subsequently, Airbus Helicopters is developing a compound helicopter, called RACER, as a Clean Sky2 project.[6] Sikorsky Aircraft designed the X2TD and demonstrated high-speed flight.[7-8]

In this study, a "level flight" multi-rotor aircraft, a concept for a high-speed multi-rotor aircraft characterized by a horizontal attitude during forward flight, using a separately placed propeller for propulsion is investigated. As a similar design, Aergility ATLIS[9] utilizes motors to power eight “Managed Autogyration” vertical propellers for take-off and landing, while a gas powered pusher prop propels it forward and the vertical propellers go into a gyrocopter mode for lift. The concept proposed here is more similar to the lift-offset coaxial rotors. For the rotors used in multirotor aircraft, no cyclic pitch angle mechanism is provided. During forward flight, such kind of rotors will naturally get into a state of lift-offset. Relative higher lift-to-drag ratio can be expected.

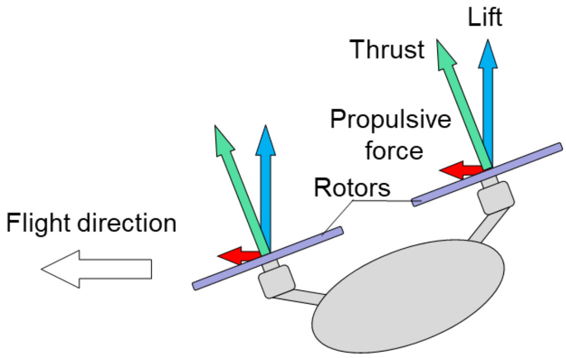
Figure 1 shows the configurations of a conventional multi-rotor aircraft (a) and a level-flight multi-rotor aircraft (b). In the conventional multi-rotor aircraft, the fuselage is tilted forward during forward flight, and the thrust generated by the rotor is partially used for propulsion.[10] The forward tilt of the fuselage generates a significant drag due to the increase in the projection area. In addition, the propulsion provided by the rotor is limited to the balance between lift and gravity. The horizontal rotor configuration avoids the increase in drag caused by the forward tilt of the aircraft. Therefore, it is expected to reduce the drag and increase the flight speed.

For another feature of the proposed level-flight multi-rotor aircraft, a dual-controlled rotor system is proposed in this study. This system controls the rotational speed and blade pitch angle of the rotor at the same time. The rotor is controlled only by the rotational speed in conventional multirotor aircraft [10]. By controlling the rotational speed and pitch angle

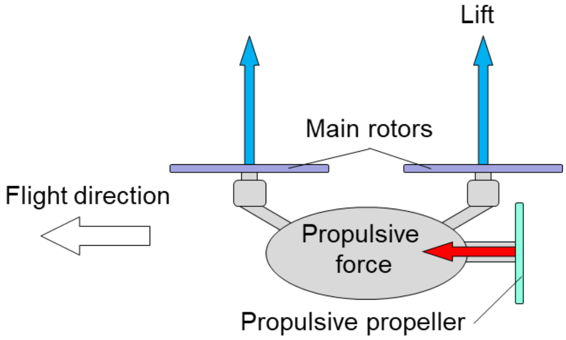
Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

simultaneously, various operating conditions of the rotor can be selected while keeping the lift constant. Thus, it is possible to control the operating conditions of the rotor to achieve optimal aerodynamic performance according to the flight conditions of the multi-rotor aircraft.

The purpose of this paper is to investigate the aerodynamic performance of the proposed dual-controlled rotor in high-speed flights. The aerodynamic performance is evaluated through numerical simulation in this study. The aerodynamic performance of the horizontal rotor is compared with the forward tilting rotor. The effect of blade twist on the aerodynamic performance in forward flight is also investigated.



(a) Forward tilt type



(b) Compound type

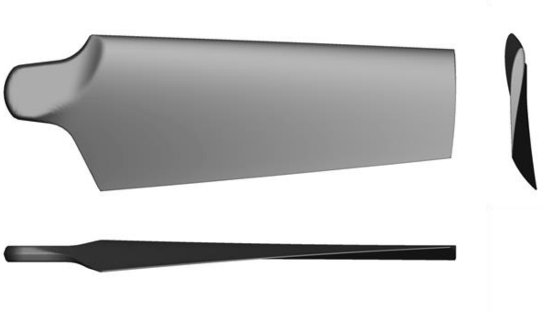
Figure 1. Configurations of multi-rotor aircraft.

2. NUMERICAL SIMULATION

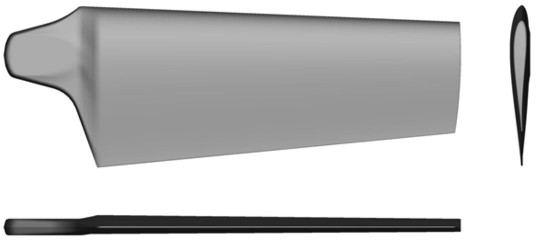
2.1. Computational Model

The aerodynamic performance of a single rotor is investigated in this paper. The rotor blades utilize the blade designed for variable-pitch-controlled multiple-rotor drones.[11] This rotor blade is designed to achieve high hovering efficiency when performing bridge inspections and other tasks. The number of rotor blades is two, and the radius is 0.1905 m. The nominal rotational speed is 5400 RPM. The blade twist is linear distribution of -21 degrees. The OAF117 airfoil is adopted. To investigate the effect of the blade twist on the aerodynamic performance in forward flight, the blade with the same planform but untwisted is considered. The two blade designs are shown in Fig. 2. Table 1 summarizes the rotor specifications used in this study.

In this study, the rotor has a variable pitch mechanism that changes the blade pitch angle. The lift of the rotor can be adjusted by the blade pitch angle and rotational speed of the rotor at the same time.



(a) Twisted blade



(b) Untwisted blade

Figure 2. Blade geometries.

Table 1 Specifications of the rotor blades

Number of blades	2
Rotor radius	0.1905 m
Blade tip chord	0.0402 m
Taper ratio	0.6
Blade twist	-21 / 0 degrees
Airfoil	OAF117
Nominal RPM	5400 RPM

2.2. Numerical Method

The aerodynamic performance of the rotor is evaluated using a rotorcraft CFD solver, rFlow3D [12-15], developed at Japan Aerospace Exploration Agency (JAXA). The governing equations are the three-dimensional compressible Navier-Stokes equations. The finite volume method is used for spatial discretization. A moving overlapped grid is adopted to the computational grid, which can be used to calculate the flowfield around the rotating blades. For time integration, the explicit four-stage Runge-Kutta method is applied to the Cartesian background grid, and the dual-time stepping method and LU-SGS implicit method are utilized to the body-fitted blade grid. The numerical flux is calculated by the mSLAU (modified Simple Low-dissipation AUSM) method, which is an all-speed scheme. The viscous flux is computed using a second-order central difference scheme. Since the Reynolds number is 2×10^5 and the boundary layer is not considered to be fully turbulent. The turbulence model is not used in this study.

The trim analysis is carried out to adjust the rotor thrust, T. The blade pitch angle, θ, is updated using the following equation.

$$\Delta\theta = \frac{\partial T}{\partial \theta}\Delta T \qquad (1)$$

$$\Delta T = T_{target} - T_{CFD} \qquad (2)$$

The derivative in Eq. (1) is numerically obtained based on the blade element theory. The calculation is repeated until the target rotor thrust is obtained.

2.3. Computational Setup

The aerodynamic performance of the rotor is evaluated assuming forward flight conditions. Two flight conditions are considered: 32 m/s, which is around the maximum speed the multiple-rotor drone is capable of flying, and 64 m/s, which is double that speed. The required rotor lift in this study is 17.16 N, which is obtained from the quadrotor drone in a previous study. [11] The trim analysis adjusts the blade pitch angle to obtain the target lift of the rotor. Table 2 summarizes the assumed flight conditions in this study.

Table 2 Assumed flight conditions

Flight condition	Forward flight
Flight speed	32, 64 m/s
Required rotor lift	17.16 N

The overlapping grid system used in this study is shown in Fig. 3. The outer and inner background grid is used to capture the vorticity flowfield around the rotor. These background grids are Cartesian grids. The outer background grid has non-uniform grid distribution, and the inner background grid has a uniform grid distribution. The grid size of the inner background grid is 15% of the blade tip chord length.

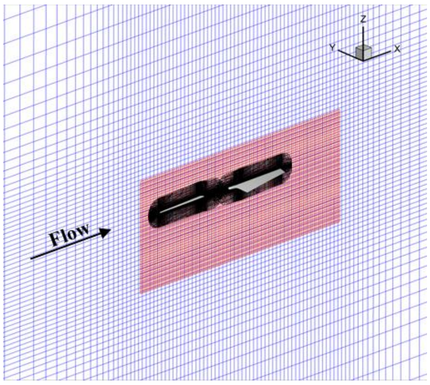


Figure 3. Computational grids

3. RESULT AND DISCUSSION

3.1. Effect of tilt angle on the rotor performance

In a typical multi-rotor aircraft, propulsive force is generated by tilting the rotor disk forward to perform forward flight. The lift, L, and propulsive force, X, of the rotor tilted forward are obtained as follows.

$$L = T\cos\alpha + H\sin\alpha \qquad (3)$$

$$X = H\cos\alpha - T\sin\alpha \qquad (4)$$

Where T is the rotor thrust, H is the horizontal force relative to the shaft axis. In this section, the aerodynamic performance of the forward tilting rotor is discussed. The twisted rotor blade is used to evaluate the forward tilting rotor. The rotor rotational speed is set to a nominal 5400 RPM, and the flight speed is 32 m/s. The forward tilt angle of 0, 10, 20, 30, 45 degrees are investigated.

The relationship between the rotor tilt angle and the effective lift-to-drag ratio is shown in Fig. 4. The data are plotted in the same lift condition. The effective lift-to-drag ratio is a ratio of the lift, L, to effective drag, D_e. The effective drag is defined as follows.

$$D_e = \frac{P}{V} - X \qquad (5)$$

$$X = -D \qquad (6)$$

Where P is the rotor power, V is the flight speed, and D is the drag of the rotor.

From Fig. 4, it can be seen that the horizontal rotor has the highest effective lift-to-drag ratio and that the effective lift-to-drag ratio decreases as the tilt angle increases.

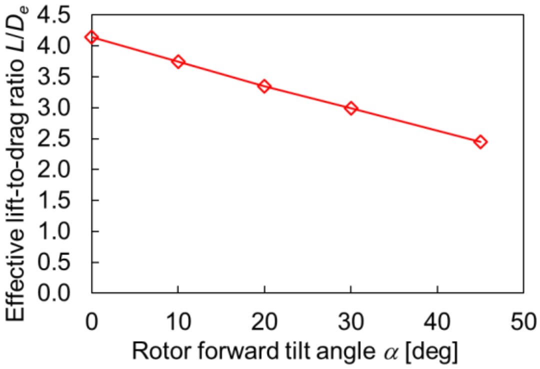


Figure. 4 Effective lift-to-drag ratio for rotor forward tilt angle.

In order to discuss the decrease in the effective lift-drag ratio due to this increase in the forward tilt angle, the components of the effective drag are considered. Figure 5 shows the relationship between the rotor tilt angle, the rotor power component, P/V, and the rotor propulsive force, X. The forward tilt of the rotor generates the propulsive force, and the propulsive force also increases with the increase in the forward tilt angle. It can also be seen that the rotational power increases with the increase in the tilt angle. This is because the forward tilt of the rotor increases the required rotor thrust to satisfy the same lift condition. It is suggested that forward flight performance is enhanced by making the rotor plane horizontal.

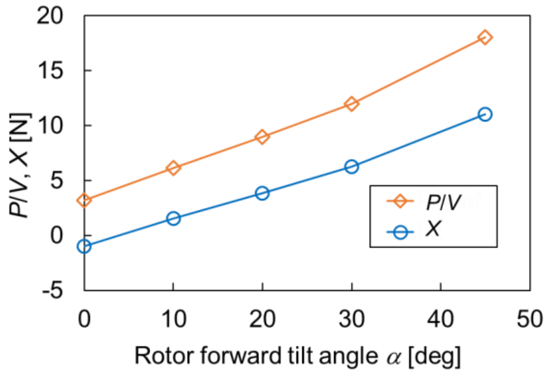


Figure 5. Power and propulsive force of the rotor against rotor tilt angle

3.2. Effect of dual-control

The previous section observed that high rotor performance could be obtained with a horizontal rotor in forward flight. In this section, the impact of the dual-control system, which simultaneously changes the rotational speed and pitch angle of the rotor, on the aerodynamic performance of the rotor is discussed. By varying the rotational speed of the rotor, the aerodynamic environment of the rotor changes significantly. The advance ratio of the rotor changes, resulting in the size of the reverse flow region on the blade retreating side changes. Also, by varying the rotational speed, the lift offset state occurs and improves the aerodynamic performance of the rotor. This paper focuses on the effect of the proposed dual control system on rotor performance. The relationship between flow fields and lift offset will be studied in future works.

The impact of the dual-control system on the rotor performance is investigated using the twisted blade under the conditions of 32 m/s and 64 m/s. The rotor disk is horizontal to the flow, and the rotational speed is changed to evaluate the aerodynamic performance. At 32 m/s, the rotational speed is varied between 3600 RPM and 7200 RPM. Also, at 64 m/s, the rotational speed is varied between 2400 RPM and 7200 RPM. The advance ratios of the rotor are 0.22 to 0.45 at the condition of 32 m/s, and 0.45 to 1.34, which is high advance ratio, at the condition of 64 m/s. The blade pitch angle is controlled to achieve a constant lift of 17.16 N at different rotational speeds.

Figure 6 shows the effective lift-to-drag ratio of a dual-controlled rotor. When blade pitch angle control is not considered, a blade pitch angle of 9.0° during hovering at the rated speed of 5400 RPM is assumed to be the standard for the fixed pitch rotor. The Dual-control system improves the effective lift-to-drag ratio from about 3.9 to 4.2 at 32 m/s and about 4.5 to 5.7 at 64 m/s compared to the fixed pitch rotor. It is found that the effective lift-to-drag ratio can be improved while keeping the lift constant by controlling the rotational speed and the blade pitch angle simultaneously. This improvement in the effective lift-to-drag ratio is discussed from the drag and the rotational power at 64 m/s.

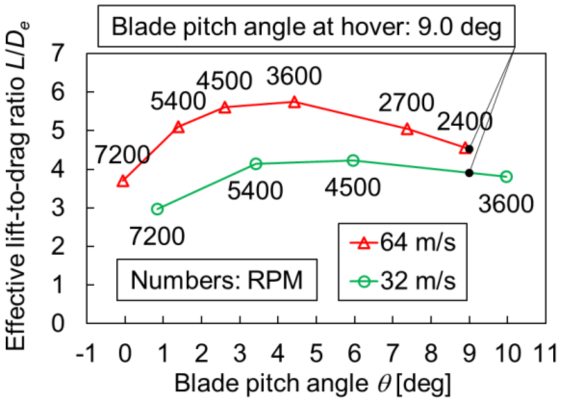


Figure 6. Comparison between effective lift-to-drag ratios and blade pitch angle of dual-controlled rotor.

Figure 7 shows the drag and the power component at 64 m/s. It can be seen that the drag force is reduced, and the rotational power is increased by dual control, which increases the rotational speed and decreases the blade pitch angle, compared to the condition similar to the fixed pitch rotor condition. The increase in the rotational power is considered to be dominated by the increase in the rotational speed. The optimal value of the effective drag is determined by the relationship between the power and the drag, and the optimal point is 3600 RPM before the respective values increased rapidly in this study.

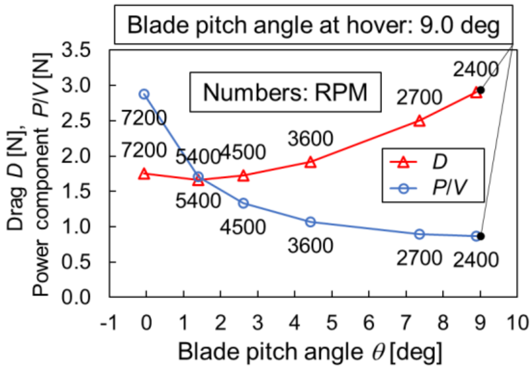


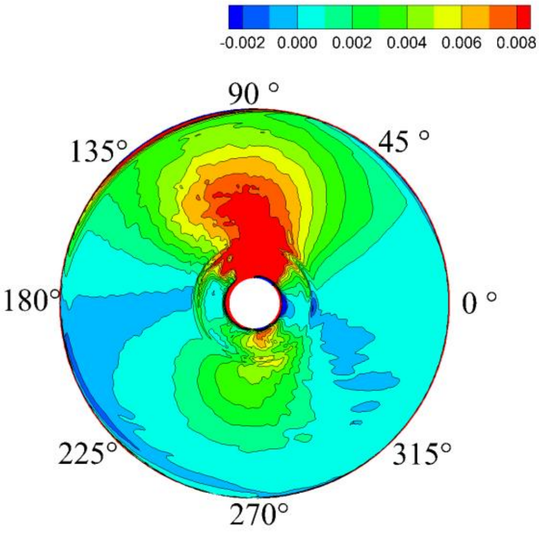
Fig. 7 Comparison between components of effective drag and blade pitch angle of dual-controlled rotor.

Figure 8 shows the $C_x M^2$ distribution at 2400 and 3600 RPM. $C_x M^2$ is the sectional drag force on the blade relative to the shaft axis.

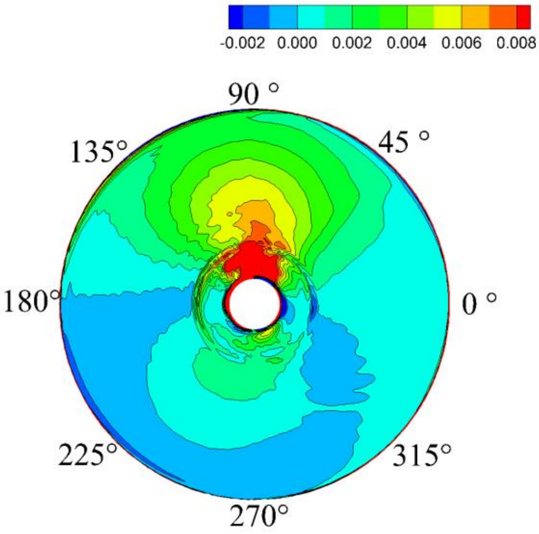
$$C_x M^2 = \frac{f_x}{1/2\,\rho a^2 c} \tag{7}$$

Where f_x is the sectional drag force on the blade relative to the shaft axis, ρ is air density, a is sound speed, c is the blade chord length. The drag force decreases with the increase in rotational speed of the rotor on both the advancing and retreating sides, as shown from Fig. 8. The blade pitch angle decreases to produce the same lift by increasing rotational speed. Thus, the induced drag on the blade is reduced due to the reduction of the pitch angle.

Therefore, the dual-control system indicated that the performance improvement can be obtained by providing the optimal rotational speed and pitch angle of the blade to match the flight speed. The numerical results show that the reduction of rotational speed associates with the decrease in the rotor power. The reduction of the blade pitch angle contributes to the decline of the drag of the rotor.



(a) 2400 RPM, $\theta = 8.9°$



(b) 3600 RPM, $\theta = 4.4°$

Fig. 8 $C_x M^2$ distribution of different dual-control conditions.

3.3. Effect of blade twist

The aerodynamic performance between the twisted and the untwisted blades are compared to investigate the effect of blade twist on the rotor performance. The drag of the rotor significantly contributes to the effective lift-to-drag ratio of the rotor. The twisted blade is designed to achieve highly hovering efficiency and has a high twist angle. For forward flight, a high twist angle causes significant parasite drag and reduces the aerodynamic performance.

The aerodynamic performance of the rotor is evaluated at a flight speed of 64 m/s. The rotational speeds of both rotors are 2400 to 7200 RPM for the twisted blade and 2700 to 7200 RPM for the untwisted blade. The rotor disk is horizontal to the freestream velocity. The blade pitch angle is controlled to achieve a constant lift of 17.16 N at different rotational speeds.

Figure 9 shows the comparison of the effective lift-drag ratios between the twisted and the untwisted blades. The effective lift-to-drag ratio is about 5.7 for the twisted blade but increases to 6.8 for the untwisted blade. The effective lift-to-drag ratio can be improved by reducing the blade twist.

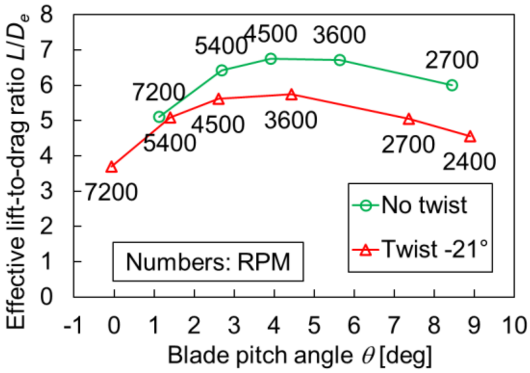
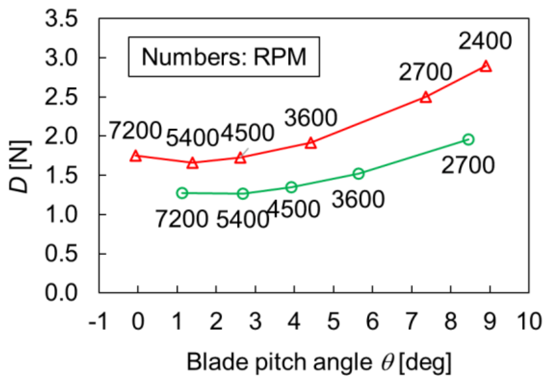
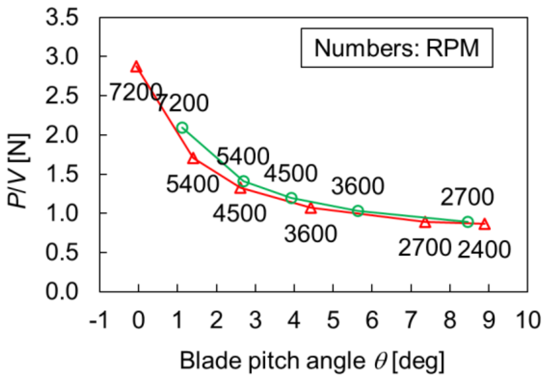


Figure. 9 Comparison between effective lift-to-drag ratio and blade pitch angle between twisted and untwisted blades.

Figure 10 shows the comparison of the drag of the rotor and the rotor power at 64 m/s. The drag of the rotor drastically reduces by eliminating twists. On the other hand, there is no significant difference in rotor power between both blades. It is indicated that the effect of the blade twist on the rotor power is small, and the effect of rotational speed is significant.



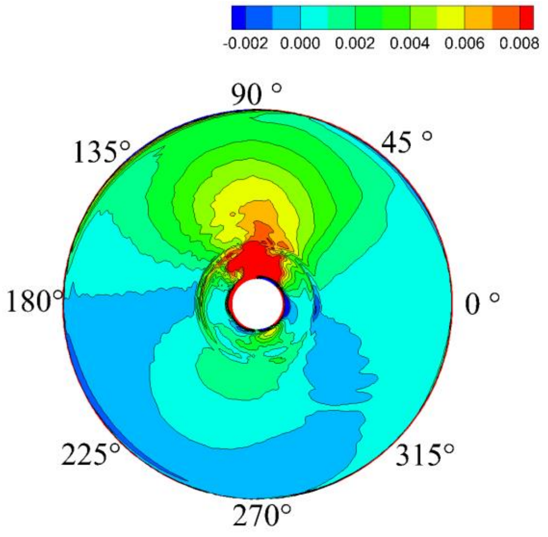
(a) Comparison between drag and blade pitch angle.



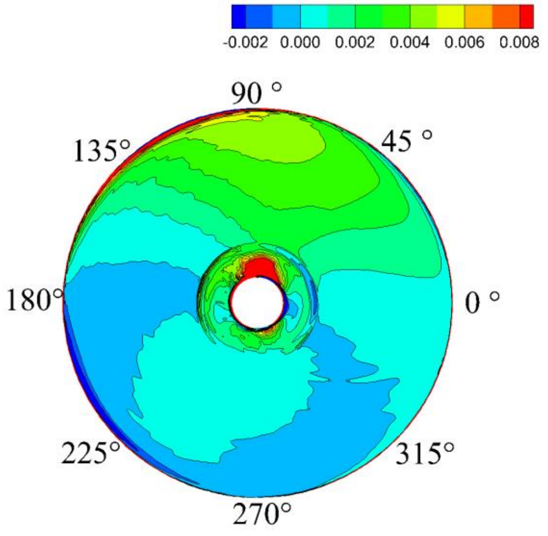
(b) Comparison between power component and blade pitch angle

Figure 10 Comparison between effective drag components and blade pitch angle of blades with and without twist.

Figure 11 shows $C_x M^2$ distribution for both twisted and untwisted blades at 3600 RPM. The drag of the twisted blade is large in the region where the radial positions of both the advancing and retreating sides are small. This is because the local blade pitch angle of the twisted blade is large in the inboard region and the dynamic pressure is higher on the blade advancing side.



(a) Twisted blade



(b)Untwisted blade

Figure 11. Comparison of $C_x M^2$ *distributions between the twisted and untwisted blades at 3600 rpm.*

4. CONCLUSION

We investigated the performance of a single rotor in forward flight through numerical simulations to demonstrate the advantage of a conceptual "level flight" multi-rotor aircraft. For further improvement of aerodynamic performance, we proposed a dual-controlled rotor system, whose control parameters are rotational speed and blade pitch angle. The rotor blades utilize the designed blade for variable pitch multiple-rotor drones. This rotor blade is designed to achieve high hovering efficiency. In order to evaluate the aerodynamic performance of the horizontal rotor, the effects of (1) forward tilting, (2) dual-control system, (3) twist on the aerodynamic performance of the rotor in forward flight are investigated, and the following findings are obtained.

1. The effective lift-to-drag ratio of the horizontal rotor is higher than that of the forward-tilted rotor.
2. A dual-controlled rotor improves the effective lift-to-drag ratio. The optimal value of the effective drag is determined by the relationship between the power and the drag. The rotational speed contributes to changing the rotor power, and the drag reduction depends on the blade pitch angle.
3. The effective lift-to-drag ratio of the untwisted blade is higher than that of the twisted blade. The blade twist affects the drag of the rotor.

REFERENCES

[1] Ventura Diaz, P., Caracuel Rubio, R., and Yoon, S., “Simulations of Ducted and Coaxial Rotors for Air Taxi Operations", AIAA Paper 2019-2825, The AIAA Aviation Forum 2019, (2019).

[2] Ventura Diaz, P. and Yoon, S., “Computational Study of NASA's Quadrotor Urban Air Taxi Concept", AIAA Paper 2020-0302, The AIAA SciTech Forum 2020, (2020).

[3] Ventura Diaz, P., Yoon, S., and Theodore, C.R., “High-Fidelity Computational Aerodynamics of the Elytron 4S UAV”, The AHS International Technical Meeting on Aeromechanics Design for the Transformative Flight, (2018).

[4] Ventura Diaz, P. and Yoon, S., “A Physics-Based Approach to Urban Air Mobility", The European Rotorcraft Forum, Paper 18, (2018).

[5] Giovanetti, E.B., “Optimal Aerodynamic Design of Conventional and Coaxial Helicopter Rotors in Hover and Forward Flight”, Duke university master thesis, (2013).

[6] Blacha, M., Fink, A., Eglin, P., and Cabrit, P., “Clean Sky2: Exploring New Rotorcraft High Speed Configurations,” The European Rotorcraft Forum, Paper 593_ERF2017, (2017).

[7] Bagai, A., “Aerodynamic design of the X2 Technology DemonstratorTM main rotor blade”, the 64th Annual forum of the American Helicopter Society, (2008).

[8] Walsh, D., Weiner, S., Arifian, K., Lawrence, T., Wilson, M., Millott, T., and Blackwell, R., “High Airspeed Testing of the Sikorsky X2 TechnologyTM Demonstrator,” The American Helicopter Society 67th Annual Forum, (2011).

[9] “Aergility Atlis.” Electric VTOL News™, Vertical Flight Society, https://evtol.news/aergility-atlis/.

[10] Mahony, R., Kumar, V., and Corke, P., "Multirotor Aerial Vehicles: Modeling, Estimation, and Control of Quadrotor," in IEEE Robotics & Automation Magazine, vol. 19, no. 3, pp. 20-32, Sep3012, doi: 10.1109/MRA.2012.2206474.

[11] Yonezawa, K. Matsumoto, H., Sugiyama, K., Tanabe, Y., Tokutake, H., and Sunada, S., “Aerodynamic Characteristics of a Quad-Rotor-Drone with Ducted Rotors,” 8th Asian/Australian Rotorcraft Forum, Ankara, Turkey, Oct. 30-Nov. 2, 2019.

[12] Tanabe, Y., and Saito, S., "Significance of all-Speed Scheme in Application to Rotorcraft CFD Simulations," 3rd International Basic Research Conference on Rotorcraft Technology, (2009).

[13] Tanabe, Y., Saito, S., Takayama, O., Sasaki, D., and Nakahashi, K., "A New Hybrid Method of Overlapping Structured Grids Combined with Unstructured Fuselage Grids for Rotorcraft Analysis," 36th European Rotorcraft Forum, (2010).

[14] Tanabe, Y., Saito, S., and Sugawara, H., "Evaluation of Rotor Noise Reduction by Active Devices Using a CFD/CSD Coupling Analysis Tool Chain," 1st Asian/Australian Rotorcraft Forum, (2012).

[15] Tanabe, Y., Saito, S., and Sugawara, H., "Construction and Validation of an Analysis Tool Chain for Rotorcraft Active Noise Reduction," 38th European Rotorcraft Forum, (2012).