Thrust Loss Saving Design of Overlapping Rotor Arrangement on Small Multirotor Unmanned Aerial Vehicles

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***Abstract*— Small multirotor unmanned aerial vehicles (UAVs) are suitable for surveillance or inspection operations, such as disaster site observations or building inspections, as they can hover. Therefore, engineers and associations plan to use them for civilian applications. However, the payload capacity of current UAVs is too small to carry heavy sensors or batteries. Thus, improving payload capacity by increasing the number of rotors has been considered to achieve an increase in the thrust for a limited body size. Although, most rotor arrangements cause rotor flow interaction, which degrade the total thrust. To design a rotor arrangement on small multirotor UAVs, it is necessary to first evaluate the thrust from an aerodynamic perspective. In this study, we evaluated the effect of rotor flow interactions on thrust for three two-rotor configurations. The investigation showed that the thrust of rotors in wake flow is degraded. Thus, we proposed a new octorotor UAV configuration based on the results of our evaluation of the rotor flow interaction and verified the thrust improvement compared to a coaxial octorotor UAV configuration. This investigation demonstrated a thrust improvement of 24% over the total thrust of the coaxial octorotor UAV.**

I. Introduction

Engineers and associations plan to use small multirotor unmanned aerial vehicles (UAVs) for civilian applications, such as transporting medical kits, surveilling disaster sites, and inspecting old highway bridges. These UAVs are vertical takeoff and landing (VTOL) aircraft and can hover at specific points in the air as shown in Fig. 1. The UAVs are attractive for civilian application because of their hovering ability, user-friendly flight controllability, and low manufacturing cost compared to previous small VTOL UAVs. The ability of the UAVs to hover in flight renders them suitable for investigation activities and enables pilots to control their flight easily, as their movement is slow compared to fixed-wing UAVs. Moreover, the UAVs can realize 6-degree-of-freedom movement by controlling only the rotational speeds of multiple rotors of the same size. The simple architecture decreases manufacturing cost and has expanded the market for these UAVs from military to civilian applications.

Although multirotor UAVs are suitable for civilian applications, technological improvements are required to increase their payload capacity, extend their endurance, and improve their posture stability in cross-winds. Among those problems, the lack of sufficient payload capacity is critical for applications that require increasing the battery weight or equipping the UAV with heavy sensors. Therefore, engineers focus on increasing the total rotor thrust of the UAVs. Extending the rotor diameter is the simplest method to increase thrust, but it requires an increase in the body size in the diameter of the outer circumference. Considering flight in limited space as indoor flight and transportability to surveying sites by an automobile or a small container, expanding the rotor diameters is not the preferred solution. Increasing the number of rotors can also increase thrust at the same supplied voltage from a battery. Therefore, coaxial rotors are applied to the UAVs. However, the increase in thrust from applying coaxial rotors to the UAVs is smaller than the thrust increase that can be obtained with the same number of independent rotors. This is caused by flow interaction between the rotors and has been investigated in detail in aerodynamic researches [1] [2] [3]. Nevertheless, small multirotor UAV designs hardly reflect the aerodynamic research results. Moreover, aerodynamic evaluation on flow interaction of small scale rotors for multirotor UAVs is not sufficient compared to manned scale VTOLs, in particularly evaluation on flow interactions of small plural rotors over three rotors. Therefore, evaluation on the effect of rotor flow interaction for a narrow-body UAV is needed to design large-payload UAVs with limited body size in the diameter.

Figure 1. A small quadrotor UAV.

The objectives of the present research are to evaluate the rotor thrust affected by rotor flow interaction for multirotor UAVs, and to design a rotor arrangement based on the results of the evaluation to achieve an increase in the total thrust of the UAVs, while maintaining their limited size. In the study, we first elucidated how rotor thrust was affected by rotor flow interaction between two rotors. We then proposed an octorotor UAV configuration based on the evaluation results and verified the total thrust of the proposed configuration.

The present paper is organized as follows. Sec. II

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discusses basic rotor theories and previous research on rotor flow interactions. Sec. III presents the evaluation of rotor thrust in flow interactions. In Sec. IV, a new design of an octorotor configuration considering rotor arrangement is proposed, and an experimental evaluation of the configuration is presented.

II. THEORY

Before evaluating the rotor flow interaction effect on rotor thrust, we review the basis of rotor thrust and interaction of rotor flows.

A. Rotor Thrust and Advance Ratio

The thrust and required rotation power of a rotor rely on the radius (R, m), the rotational speed of the rotor (Ω, rad/s), the air density, and the Reynolds number [4] [5], as below

$$T = C_{\mathrm{t}} \rho A (\Omega R)^2. \tag{1}$$

$$P = C_{\mathrm{p}} \rho A (\Omega R)^3. \tag{2}$$

In (2) and (3), the thrust and power depend on the dimensionless thrust coefficient (C_t) and power coefficient (C_p). C_t and C_p depend on the rotor shape and the Reynolds number. Most rotor evaluation experiments use C_t and C_p to compare performance among different rotors. However, we did not use these numbers in our current study because we used identically shaped rotors, and these expressions yield the same results for rotors of the same shape. In addition, C_t is not familiar to robotics engineers. In the case of discussions for rotor performance for different shapes, we should use C_t and C_p. Considering endurance of the UAVs, we can evaluate the hover performance on the rotors using the figure of merit which is calculated from C_t and C_p [4].

Besides, the rotor thrust changes as the ratio of intake flow velocity to rotation speed changes. In rotor aerodynamics, the speed is replaced with the free stream velocity (V, m/s), and the ratio of them is expressed as the advance ratio (μ) as in (3):

$$\mu = V / \Omega R. \tag{3}$$

Generally, the rotor thrust decreases as the advance ratio increases [6]. This means that rotor thrust decreases in accelerated flow, such as downstream of an airplane propeller. Therefore, rotor flow interactions serve to change the rotor advance ratio and change the thrust of the rotors as a lower rotor of VTOLs with multiple rotors.

B. Rotor Flow Interactions

Rotor flow interactions were investigated for manned VTOLs with multiple rotors such as CH-46 or MV-22. For instance, Ghost analyzed the ground effect of realistic VTOLs with multiple rotors using computational fluid dynamics (CFD) [7]. One of the multiple-rotor configurations that has received attention is the coaxial rotor arrangement. The coaxial rotor concept appeared before the 20th century, and a large number of investigations were conducted. Taylor visualized the flow of coaxial and biaxial rotors [1], which is meaningful for the consideration of rotor flow interactions. His visualization result demonstrated how the upper-rotor flow wake enters the lower rotor. The visualized flow of coaxial rotors is shown in Fig. 2. Therefore, flow interaction due to the

Figure 2. Visualized flow of coaxial rotor[1].

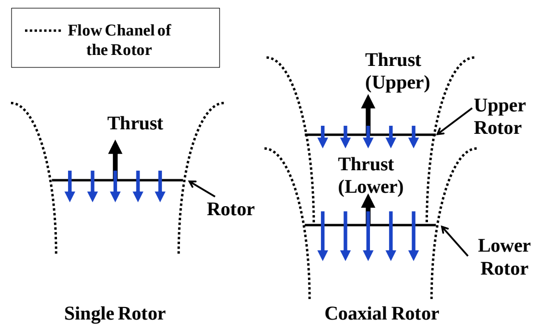

Figure 3. Flow model of an isolated rotor and a coaxial rotor[2].

upper rotor flow seems to degrade the lower-rotor thrust in coaxial rotors. Stepmiewski conducted a model-rotor measurements and reported experimental results on thrust of overlapping twin rotors [8]. Harris summarized Stepniewski's experimental results and theories [9]. Payne explained degradation of overlapping rotors thrusts using expanded momentum theory [10]. Coleman summarized details of coaxial rotors [11]. Lishman and Ananthan designed optimized coaxial rotors using blade-element momentum theory and explained the flow model of a coaxial rotor [2]. A flow model of coaxial rotors compared to an isolated rotor is shown in Fig. 3. Lishman and Beader investigated the performance of coaxial rotors using a compressible Reynolds Averaged Navier Stokes solver in a CFD analysis [12]. They confirmed the degradation of thrust of lower rotors at the same rotational speed and collective pitch of the rotors. Thus, previous research is in agreement that flow interaction of coaxial rotors degrades lower-rotor thrust. Based on previous research results, we assumed that the total thrust of the rotors degrades when rotors overlap. Thereby, we need to investigate how much overlap effects to the thrust of multirotor UAVs to design it.

From the perspective of analyzing the rotor flow of small multirotor UAVs, insufficient investigation has been reported. A few CFD analyses have revealed the flow structure of small multirotors. Aleksandrov and Penkov calculated the rotor flow for standard small quadrotor UAVs and investigated how thrust changes with extending the rotor shaft distance [13]. Hwang reported on flow structures of a quad-rotor UAV in hover and cruise flight [14]. However, the flow structures of other types of multirotor UAVs have not been investigated in detail. Moreover, there has been insufficient experimental investigation into the flow interaction for small multirotor UAVs, compared to full-scale VTOLs.

In short, aerodynamic evaluations have been conducted on the flow interactions of rotors for coaxial rotors and full-scale VTOLs. The results show a degradation of rotor thrust as a result of rotor overlap. On the other hand, rotor flow investigations for small-scale rotors have not been completed. Therefore, flow interactions of small rotors must be evaluated to optimize the rotor arrangement of small multirotor UAVs.

III. Evaluation of Rotor Flow Interaction

One of the objectives of this study is to evaluate how rotor thrust is affected by rotor flow interaction on multirotor UAVs. Thus, we measured the thrust of two rotors in three arrangement conditions to clarify how thrust changes with changing rotor positions. Because our focus was the thrust at constant input voltage to the motors, we did not measure the mechanical power for rotation. Additionally, we did not evaluate the performance in terms of the ratio of thrust to consumed power, which is a figure of merit because we focus on only increasing the thrust not extending the endurance.

A. Measurement Method of Thrusts

Rotors: We used 239-mm rotors for our measurements, as shown in Fig. 4. The rotors are used for DJI Phantom2 multirotor UAVs. Their rotor shaft distance on a diagonal axis is 450 mm. For our experiments, we used clockwise and counterclockwise rotors. The rotational speed of the rotors was controlled by an electric speed controller within ± 10 rpm difference by using closed-loop control.

Measurement system: In the experiment, we measured thrust with a 6-axis force and torque sensor (*O34CA101, Reptlino Ltd.)*, with a maximum force range of 100 N, and a resolution of 1/4000. The sensor was attached on a measurement stand as shown in Figs. 5 and 6. In the experiments, we measured the thrust at 625 Hz for 8 seconds (5000 times) and used the average of 5000 sampled thrust data points as one measurement. For each condition, the measurement was conducted three times.

Rotors Arrangement Cases: We measured the thrust of two rotors in three different allocations: birotor, coaxial rotor, and sliding parallel rotor configurations. The positions of the rotors in the three cases are shown in Fig. 7. The rotors of multirotor UAVs are usually placed in the same plane with limited clearance between the rotor tips. To minimize the size of the UAVs, maintaining a short distance between the rotor axes is important. However, the wakes of the rotors seem to interfere on the UAVs when the rotors are close to each other. Thus, in the birotor configuration measurements, we investigated the effect of the rotor axis distance on rotor flow interaction. Coaxial rotors can generate powerful thrust for a limited UAV body size. However, their combined thrust is smaller than twice the independent rotor thrust because the rotor flows interfere. Therefore, in the case of coaxial rotor configuration, we measured the thrust at different rotor distances. In the case of sliding rotors in different planes, we investigated how the thrust changes as a function of the rotor axis distance. The objective of these measurement cases was

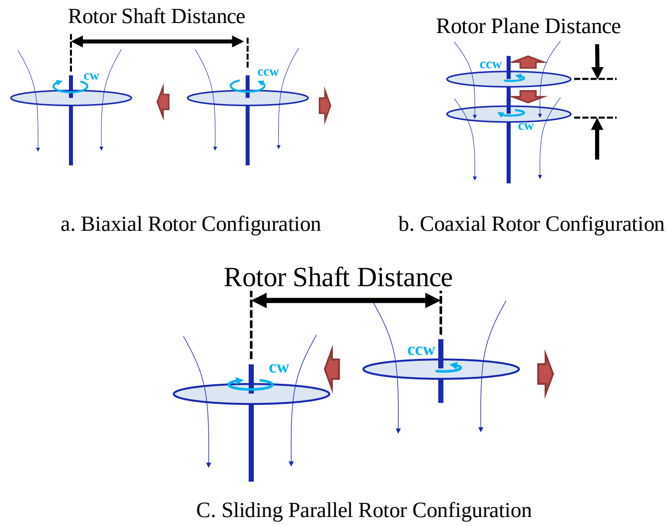

Figure 4. Rotor relative positions in the experiment.

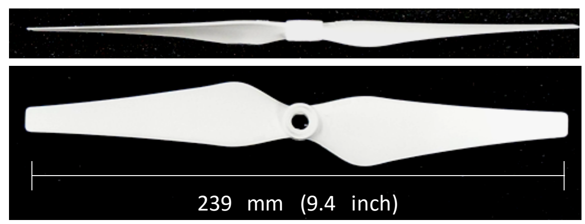

Figure 5. An experimntal rotor used for 450 mm diagonal length multirotor UAVs. (2R =239mm)

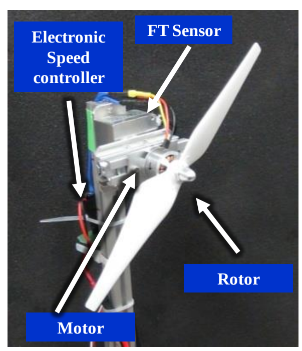

Figure 6. A rotor and a force torque sensor.

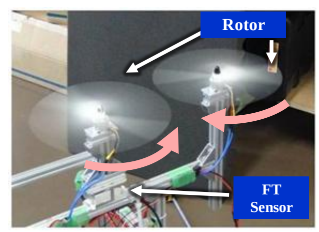

Figure 7. Biaxial rotor measureament.

to clarify the effect of rotor overlap in the limited space on the UAVs.

Measurement Conditions: The rotational speeds of the rotors were 4000 and 6000 rpm to compare flow speed differences for birotor and coaxial rotor measurements. In the sliding parallel rotor measurements, the rotor speed was 6000 rpm. The maximum rotational speed was set at 6000 rpm in the experiments to allow measuring the static force with the force and torque sensor without interference from vibration noise. At high-speed rotation, above 8000 rpm, rotors generate vibrations and cause noise in the force torque sensor. Thus, we reduced the rotational speed of the rotors relative to the typical design for multirotor UAV. In the birotor configuration case, the rotor axis distance was varied from 200 mm to 500 mm at intervals of 50 mm. In the coaxial rotor configuration case, the rotor distance was set at 50, 100, 200, 300, 400, 500, and 700 mm. The thrusts of the upper and lower rotors were measured separately. In the sliding parallel rotor case, the rotor axis distance was set from 0 to 400 mm at intervals of 50 mm, and the rotor plane distance was set at 50, 100, and 150 mm. The thrusts of the upper and lower rotors were measured separately. A summary of the measurement conditions for each case is given in Tab. 1.

B. *Experimental Results and Discussion*

Birotor Configuration: The measured thrust values for different rotor axis distances are shown in Fig. 8. The vertical line at 239 mm in Fig. 8 designates the diameter of the rotor, which means the rotor collision distance. The rotor thrusts were constant across the range of rotor axis distances in this experiment. Although rotor flow interference in birotor configuration was expected from previous flow visualization studies [1] [7], the thrusts of the rotors were nearly constant. Therefore, reducing the distance between rotor tips in the same rotor plane does not affect to rotor thrust. This means that we can minimize the size of multirotor UAVs by reducing the distance between the axes for same-plane rotors, and maintain their thrust. It should be noted, however, that shortening the rotor axis distance can lead to a reduced yawing control moment generated by the rotors.

Coaxial Configuration: The measured thrust for different rotor plane distances is shown in Fig. 9. The thrust of the upper rotors was larger than that of the lower rotors at both rotational speeds. At 6000 rpm, the lower-rotor thrust was 49% smaller than that of the upper rotor. The upper-rotor thrust was almost the same as the one for an independent single rotor. The thrusts of the upper rotor at 4000 and 6000 rpm were almost constant, independent of rotor distance. The thrust of the lower rotor at 6000 rpm increased as the rotor distance increased. From 50 mm to 700 mm distance, the thrust increased by 6%. The thrust of the lower rotor at 4000 rpm was almost constant. It was within 5% from the average thrust, with the exception of the measurement at 200 mm. The rotor distance hardly affects to recovery of the lower rotor thrust

The thrust of the upper rotor is larger than the thrust of the lower rotor, as has been reported previously. This thrust degradation seems to be caused by acceleration of the intake flow of the lower rotor. Based on this understanding, increasing the rotor distance appears to result in less acceleration of the intake flow, leading to some recovery of the lower-rotor thrust. However, the thrust of the lower rotor was almost the same as the thrust at 50 mm with increasing rotor distance. We suppose that the wake of the upper rotor hardly

TABLE.I Experimental conditions of thrust measurement for three rotor allocations.

Case. A	Biaxial Rotor Configuration
Rotor Shaft Distance	250, 300, 350, 400, 450, 500 (mm)
Rotational Speed	4000,6000 (RPM)
Case. B	Coaxial Rotor Configuration
Rotor Shaft Distance	50, 100, 200, 300, 500, 700 (mm)
Rotational Speed	4000, 6000 (RPM)
Case. C	Overlapping Rotor Configuration
Rotor Shaft Distance	50, 100, 150 (mm)
Rotor Plane Distance	0, 50, 100, 150, 200, 300 (mm)
Rotational Speed	6000 (RPM)

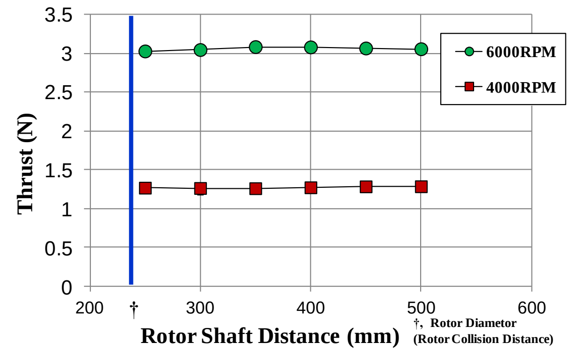

Figure 8. Thrust of biaxial rotors.

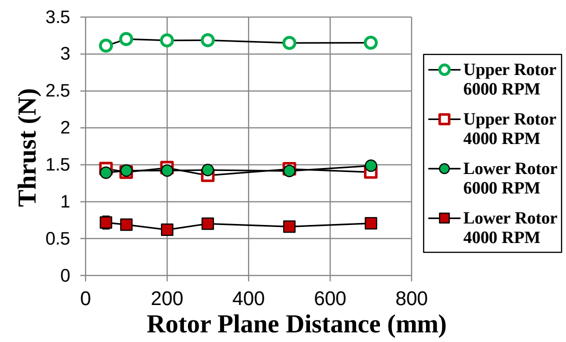

Figure 9. Thrust of coaxial rotors.

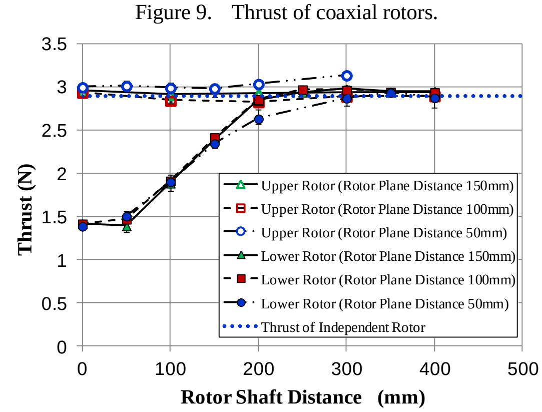

Figure 10. Thrust of overlapping rotors.

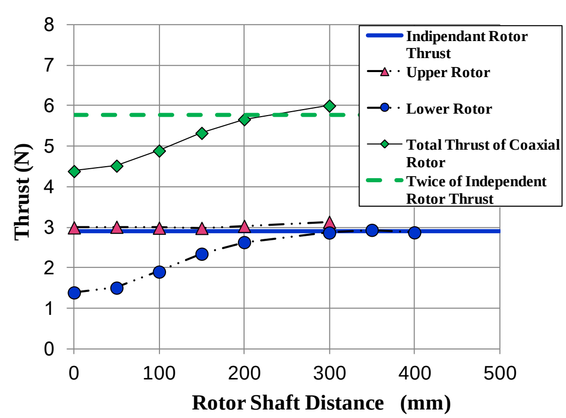

Figure 11. Thrust of overlapping rotors.

shrinks as it flows downward below the rotor, so that the intake flow speed of the lower rotor is almost constant.

Sliding Parallel Rotor Configuration: The measured thrust for different rotor axis and rotor plane distances is shown in Fig. 10. The total thrust of the coaxial rotor is shown in Fig. 11. The thrust of the upper rotor is almost constant for all rotor shaft and rotor plane distances, equal to the thrust of the independent rotor. The thrust of the lower rotor was constant across the range of rotor plane distances. On the other hand, the thrust decreased as the rotor shaft distance was reduced. The minimum thrust was recorded when the rotor shaft of both rotors coincided. At a rotor plane distance of 50 mm, the minimum thrust of the lower rotor was 46% of the independent rotor thrust. Its thrust at a rotor plane distance of 50 mm increased as the rotor shaft distance increased, recovering at 200 mm distance to 88% of the independent rotor thrust.

The lower-rotor thrust is smaller than the upper-rotor thrust, as was found for the coaxial rotor configuration. Furthermore, the lower-rotor thrust increased as the rotor shaft distance increased. This seems to be caused by a decrease in the rotor overlap area. The rotor shaft distance at which the rotor thrust recovers to above 95% of the thrust for an independent rotor is between 200 and 300 mm. This distance is equal to the rotor diameter. Therefore, we can conclude that the thrust of the lower rotor recovers as the overlap area of the rotors decreases. On the other hand, the upper-rotor thrust is constant across all rotor shaft distances. To consider the total thrust of both rotors, Fig. 11 compares the total thrust to twice the independent rotor thrust value at the 50-mm rotor plane distance. From the measured thrust at 0 mm rotor shaft distance, we confirmed that the coaxial rotor thrust is 75% of the two-independent-rotor value. This 25% decrease in rotor thrust is a fatal thrust loss for multirotor UAVs. The measurement result showed an increase in total thrust with an increasing rotor shaft distance, with a recovery of total thrust to 97% of the two-independent-rotor value.

C. Configuration of Overlapping Rotors on Multirotor UAVs

The measurement results for the three rotor arrangements clarified that rotor thrust decreases when a rotor is placed in the wake of other rotors. Therefore, the overlapping rotor and coaxial rotor configurations show a loss of total rotor thrust compared to the total thrust of the same number of independent rotors. Additionally, we confirmed that the thrust of the upper rotors hardly changes in the three arrangement cases. Thus, we should consider the degradation of the lower-rotor thrust when designing compact high-thrust multirotor UAVs.

One of the methods to avoid thrust degradation is to decrease the overlapping area of the rotors. Therefore, we should not use coaxial rotors. However, we can decrease the overlapping area by using the rotor clearance area of the upper rotors. Thus, we can improve rotor thrust performance compared to coaxial octorotor UAVs within the same UAV body size. In section IV, we propose an octorotor configuration with compact body size to increase the payload capacity of multirotor UAVs.

IV. Arrangement of Overlapping Rotors

According to the evaluation on the rotor flow interactions in the previous section, we propose an octorotor UAV configuration, which avoids rotor overlap within the configuration size in diameter of a coaxial octorotor UAV. Moreover, we evaluated the total rotor thrust in the proposed UAV design.

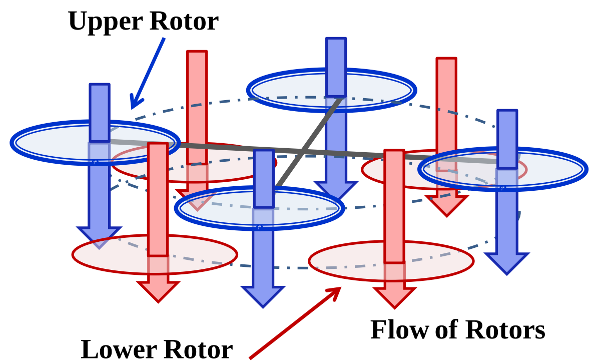

Figure 12. Concept of octorotor UAV avoiding wake interactions.

A. Octorotor Configuration in Alternate Two Rotor Plane

Octorotor UAV configurations can generate thrust from eight rotors. However, their body sizes expand to accommodate the increase in the number of rotors in the same plane. To minimize their body sizes, coaxial rotors are applied, but the total thrust of coaxial rotors is smaller than twice of the thrust of the independent rotor, as investigated in section III. Therefore, we propose an octorotor configuration in which rotors are placed in two separate planes, as shown in Fig. 12. In the configuration, we can reduce the interaction of the upper and lower rotor flows within the same body size of coaxial octorotor UAVs, by decreasing the rotor overlap area. Without expansion of the diagonal rotor axis to avoid the rotors overlapping completely, we expect that the configuration can reduce the loss of lower-rotor thrust by reducing the overlapping area of the rotors by changing an angle of rotor planes between upper rotors and lower rotors.

B. Evaluation of the Thrust of the Proposed Configuration

We evaluated the thrust of the rotors of the proposed configuration in two experiments to confirm the reduced thrust loss as compared to the thrust of the independent rotors.

Measurement Method: The rotor diameter used was 239 mm, the same as in the experiments in section III. The measurement systems in a first experiment is shown in Fig. 13. To evaluate each rotor thrust, we used only two upper rotors and one lower rotor. The measurement system of the octorotor configuration with eight rotors is shown in Fig. 14. To evaluate total thrust of the configuration, we used a full scale small octorotor UAV model, which was placed on a floor upside down to avoid the grand effect. In the experiments, the angle between the axes of the upper and lower rotors (α, °), as shown in Fig. 15, and 16, were varied

TABLE. II Experimental conditions of thrust measurement for the proposed configuration

Rotor Diagonal Axis Distance	400, 450, 500 (mm)
α, Angle of the Rotor Plane	0, 15, 30, 45 (°)
Rotational Speed	6000 (RPM)

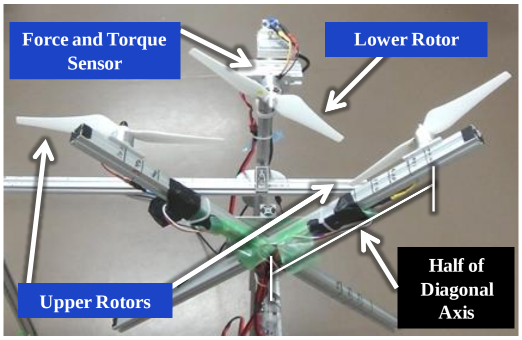

Figure 13. Measurement of thrust on two upper rotors and a lower rotor.

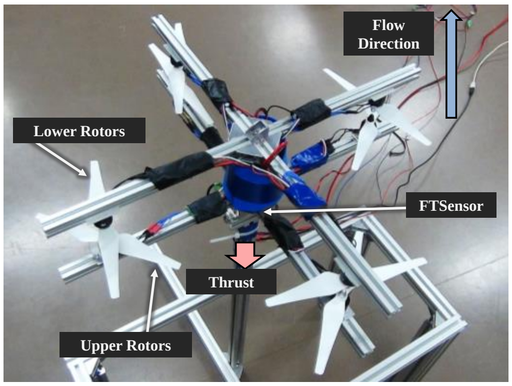

Figure 14. Measurement of octorotor UAV model thrust changing an angle of rotor planes.

from 0° to 45°. Furthermore, the rotor diagonal axis distance was set at 400, 450, and 500 mm to compare the body size and the total thrust loss. The 450-mm axis distance is most common for quadrotor UAVs. The rotor rotational speed was 6000 rpm. Measurement conditions are summarized in Tab. II.

Results and Discussions: Measurement results of each rotor thrust are shown in Fig. 17, and measurement results of the octorotor UAV model are shown Fig. 18. In Fig. 17, the independent upper-rotor thrust was constant at 2.95 N for all measurement conditions. In contrast, the upper-rotor thrust was lower than the thrust of the independent rotor. The smallest thrust of 1.4 N was measured for all the diagonal axis distances at the 0° angle, which is the same as the coaxial rotor configuration. The upper-rotor thrust was 45% of the independent rotor thrust. The lower-rotor thrust increased as the angle increased. At the 45° angle, the lower-rotor thrusts were largest. The maximum thrusts at 45° varied with the rotor diagonal axis distance. The maximum thrust increased as the axis distance increased. At 400 mm, its thrust was 68% of the independent rotor thrust. At 500 mm, its thrust was 85% of the independent rotor thrust. Extending the diagonal rotor axis and setting the angle at 45° reduced the rotor overlap area. Therefore, these results verified that the configuration could reduce the loss of thrust at the lower rotors because the rotor overlap area decreased compared to that of a coaxial octorotor UAV configuration.

This result showed individual rotor thrusts. Thus, we estimated the total thrust of the octorotor in the configuration to evaluate the loss of thrust compared to total thrust of a normal octorotor UAV, which has rotors in the same plane.

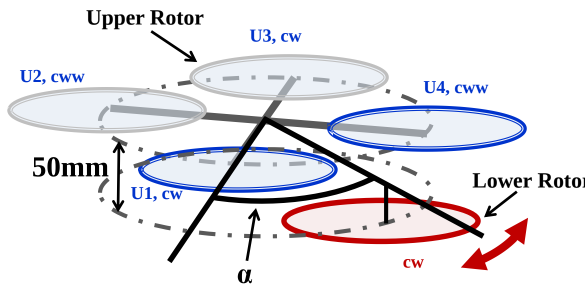

Figure 15. Details of the rotor arrangement in the experimnet with two upper rotors and a lower rotor.

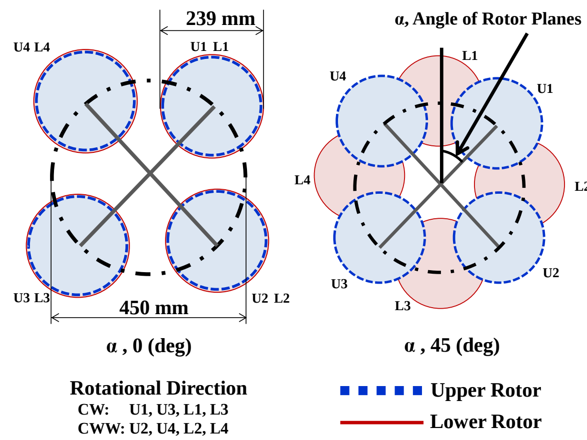

Figure 16. Top view of rotor arrangement for two angles at 450mm diagonal axis distance.

The total thrust of a normal octorotor UAV was calculated as 8 times the independent rotor thrust. Estimated total thrust of the proposed octorotor UAV configuration was calculated to be 4 times the combined thrust of the upper and lower rotors in three rotors test. The rotor positions in the total thrust estimation of the octorotor configuration at angles of 0 and 45° are shown in Fig. 16.

The estimated total thrust in each condition showed that the total thrust of coaxial rotors are from 16.6 N to 16.8 N, about 70% of the thrust of the normal octorotor configuration, for all diagonal shaft distances. In contrast, the total thrusts of the proposed octorotor UAV configuration were 84% for the 400-mm shaft distance, 89% for the 450-mm shaft distance, and 93% for the 500-mm shaft distance to the thrust of independent eight rotors. Its thrust increased as the diagonal axis was extended.

In the octorotor UAV model test as shown in Fig. 18, total thrust in each condition showed that the total thrust at an angle of 0°are from 17.4 N to 17.7 N, about 73% of the thrust of the normal octorotor configuration as almost the same as the estimated thrust. In case of avoiding overlapping at an angle of 45°, the total thrust were 85% for the 400-mm shaft distance, 90% for the 450-mm shaft distance, and 94% for the 500-mm shaft distance to the thrust of independent eight rotors.

Thus, the total thrust of the proposed configuration is larger than the total thrust of the coaxial configuration at every axis distance. At 450 mm diagonal axis length, the total thrust

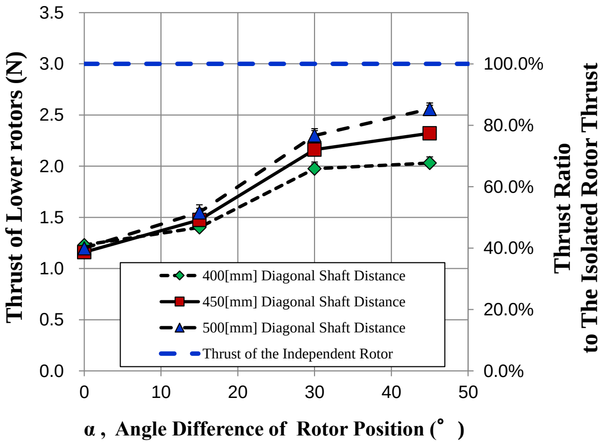

Figure 17. Thrust of a lower rotor in different configuration at 6000rpm.

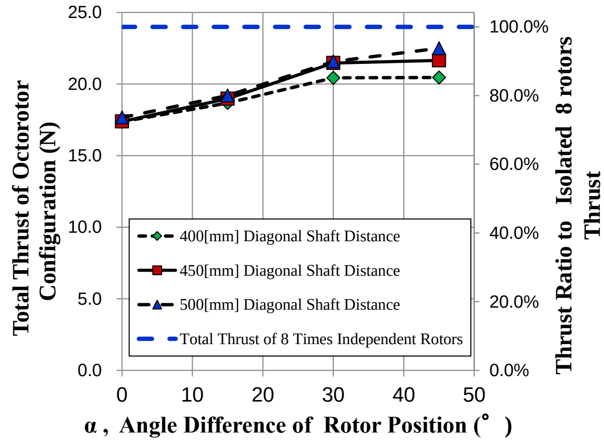

Figure 18. Total thrust of a octorotor UAV model at 6000 rpm based on experimental results.

improved between at the angles of 0 and 45° from 73% to 90% of the normal octorotor configuration thrust. These results verified that reducing rotor overlap in the proposed configuration could increase the total thrust of the octorotor UAV compared to UAVs applying coaxial rotors. Therefore, we concluded that the proposed configuration could increase rotor thrust in a limited space, considering the increased number of rotors.

V. Conclusion

Increasing the thrust of multirotor UAVs in a limited space is required to increase their payload capacity. Thus, we propose increasing the number of rotors considering flow interactions of the rotors, and proposed a new octorotor UAV configuration. In this study, we first evaluated the effect of rotor flow interference on rotor thrust in limited space for small multirotor UAVs for three configurations of the rotor positions. Secondly, we proposed a new octorotor UAV configuration concept based on the aerodynamic evaluation results and verified its total thrust.

Results of the thrust evaluation for the three rotor configurations clarified that degradation of lower-rotor thrust is caused by the deceleration of the intake flow speed of the lower rotors by flow from the upper rotors. Furthermore, the evaluation verified that the upper-rotor thrust is almost constant when rotors overlap each other and rotor flow interactions in the same plane do not significantly degrade rotor thrust. Based on this information, we suggested a design for an octorotor UAV that consists of rotors arranged alternately in two planes to avoid rotor flow interactions. Evaluation of the thrust of this concept revealed that the new conceptual configuration could generate 90% of the total thrust of 8 independent rotors at 450 mm shaft distance. The total thrust of the new concept is 24% higher than the total thrust of an octorotor UAV applying coaxial rotors, which is 73% of the thrust of the octorotor UAV. Based on these experimental results, we conclude that the proposed octorotor UAV configuration can improve payload capacity within a limited body size. However, increasing the number of rotors causes an increase in the body weight of the UAV. To design multirotor UAVs with improved payload capacity, further investigation on the relation between body weight and rotor thrust, and building and validation of a thrust calculation model are required.

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