Flow Visualization of Wake of a Quad-copter in Ground Effect

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ABSTRACT

The wake flow of a small quadcopter unmanned aerial vehicle generates a ground effect during take-off and landing. The ground effect affects the rotor thrust and posture stability. However, the structure of the wake with plural rotors has not been unveiled experimentally. In this study, the wake flow structure of a quadcopter with flow interaction between rotors was examined, and the wakes of hovering were visualized using a laser light sheet. In addition, particle image velocimetry measurements were conducted, changing ground off height and the distance between rotors. The visualization results in several planes suggested a merging wake between rotors and pulled wake at the center of the quadcopter. Furthermore, the particle image velocimetry results showed the development of a soaring flow at the center of the quadcopter in the ground effect operation, and the velocity of the soaring flow decelerated with closing rotor distance. The experimental results indicate that the soaring flow pushes the quadcopter; this flow affects the lifting force on the quadcopter during the ground effect.

NOTATION

- A area of the rotor disk, πR^2, m^2
- Ct rotor thrust coefficient, $T/\rho A\Omega^2R^2$
- Ω rotational speed of the rotor, rad/s
- ρ air density, kg/m^3
- z height of rotor above ground plane, m
- r radius of blade, m
- l distance between coincided rotors, m

INTRODUCTION

Small multirotor unmanned aerial vehicles (UAVs) are used for applications such as surveillance of disaster site, inspecting wall cracks of old bridges, and patrol drones. Similar to other vertical take-off and landing aircrafts, rotors of the small multirotor UAVs are affected by the aerodynamic interference effect produced by their wake development. Particularly, the aerodynamic interaction effect is significant when the rotors operate near the ground plane; this is known as the ground effect [1, 2]. The ground effect changes the rotors performance at take-off and landing, and causes body posture instability. However, the detailed aerodynamics of wake in multicopters have been unclear compared with the isolated rotor wake in the ground effect (IGE). The wake flow seems to contain an effect of flow interaction between rotors. We presumed that the wakes of plural rotors are different from the isolated rotor wake, and the wake structures depend on the placement of rotors. In our preliminary experiments, we confirmed that thrust of a quadcopter IGE depends on the distance between rotors. Thus, the ground effect to the rotor performance is expected to be changed with rotor configuration. Therefore, understanding the IGE wake structure is important to explain the mechanism of thrust change affected by flow interaction in the ground effect and to realize stable take-off and landing. Experimental visualization is profitable to examine rotor wake structures. It gives us hints into improving rotor placement design to reduce ground effect on the rotors and validate numerical analysis results by comparing with experimental results.

Studies concerning isolated rotor wake have conducted numerical and experimental analyses [3,4,5,6,7,8]. Komerath [9] provided an overview of the progress of investigations on rotor wake. For experimental wake flow visualization, photograph investigations using dust particles [3], shadowgraph [10,11] and particle image velocimetry (PIV) measurements [11,12] were conducted. One of the motivations of rotor wake visualization is the wake blowing flow of helicopter IGE [13,14,15]. The blowing flow causes sight loss of helicopter pilots in desert areas. Thus, the understanding of the rotor wake is important in the design of helicopters. PIV measurements were conducted intensively on rotor wake flow during IGE operations conducted intensively by the groups of researchers of in the University of Maryland led by Professor Leishman [12,11,16,17]. Lee, Leishman, and Ramasamy [17] conducted flow visualization and PIV measurement on a small isolated rotor with 86 mm radios near a ground plane. They clarified a detailed structure of the wake in and out of the ground effect. Moreover, they clarified tip vortex structures in the flow development near the ground plane with clear images. In addition to experimental investigations, numerical analyses were conducted using computational fluid dynamics (CFD) and other methods [5,18,19]. Although numerical analysis clarifies the detailed structures of wake flows, validation of the accuracy of calculation results is indispensable because

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CFD calculations on the rotor consider unsteady flow. Moreover, calculations on moving objects as rotor blades require a massive calculation cost. For multicopters wakes, flow interaction is anticipated between the wakes. Therefore, experimental visualization is indispensable to examine structures of rotor wake and is important for CFD results validation. In addition, most of the wake-flow studies focus on isolated rotor and not on plural rotors. For quad tiltrotor aircrafts, the flow interactions were assessed using CFD calculations [20,21].

The objective of the current study is to examine the wake flow structure of a quadcopter UAV in the ground effect. The wake flow affects the flow interaction between the rotors. We conducted flow visualization and PIV measurement on a quadcopter model. The experimental examination of wake structures of plural rotor configuration is important for understanding the mechanism of the ground effect and validating numerical analysis results. We selected the quadcopter configuration because it is the most popular in multicopter usages, and is the most basic configuration of numerical analysis of multicopters flow.

METHOD

We conducted flow visualization and PIV measurement on a quadcopter model. Characteristics of the flow structure were analyzed through a momentum static image during flow visualization. The averaged velocity vector maps of the wake in foul target planes were measured using the PIV test to clarify the movement of wake in different rotor configurations. The detailed method is described as follows.

Quadrotor model setup

The experiments were conducted using a quadcopter model. The model was composed of support frames, four rotors, and brushless motors as shown in Fig. 1. There was not an object, such as the body, among the rotors to examine the flow structures for avoiding the effect of flow interaction between the body and the rotor wake. The rotors were attached at the end of the support pillars to avoid flow interaction. Figure 2 shows the rotor used in the experiment. The rotor is used in commercial small multicopter UAVs. The rotor diameter is 239 mm, and the rotor speed was set at 6,000 rpm. The Reynolds number of the rotor based on 75% span chord length was 54,700. Furthermore, the chord length at 75% of the blade span was 20 mm, and the rotor solidity was 0.105. The rotor speed was controlled using an electronic speed controller. The thrust coefficient of the rotor out of the ground effect (OGE) was 0.11 at 6,000 rpm.

The experiment was conducted in a large room with sufficient space to avoid flow circulation in the room from the rotor wake. Figure 3 shows the experimental set up used in the two experiments. Except for the method of inserting smoke, most of the experimental setup was common for both the experiments. The flat floor of the setup was square, and the side length was 3,600 mm, which is 30 times that of the rotor radius (R) to avoid the effect of floor roughness.

In the experiments, we changed the distance between the rotors and rotor height from the ground plane. The rotor distance was set at 2.1 and 2.7 R; 2.1 R was close to the minimum rotor shaft distance of quadcopter configuration. The ground off height was set to 4.5 R for OGE and 0.5 R for IGE for comparison. The thrust at 4.5 R is almost the same as that out of ground plane. Thus, the value of 4.5 R was assumed as the OGE height in the experiment.

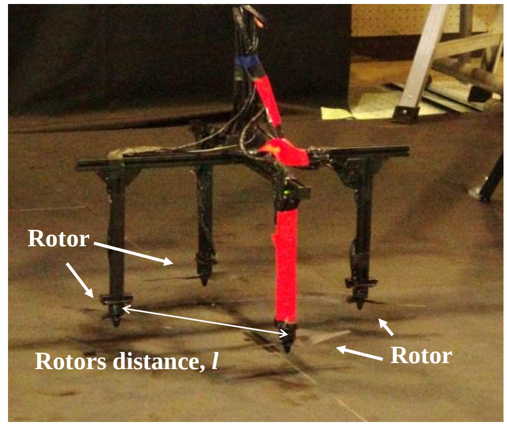

Figure 1 Experimental setup for the PIV measurement.

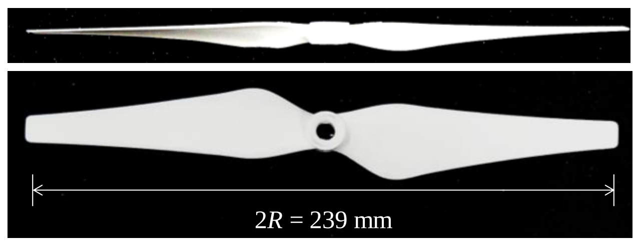

Figure 2. Experimental rotor.

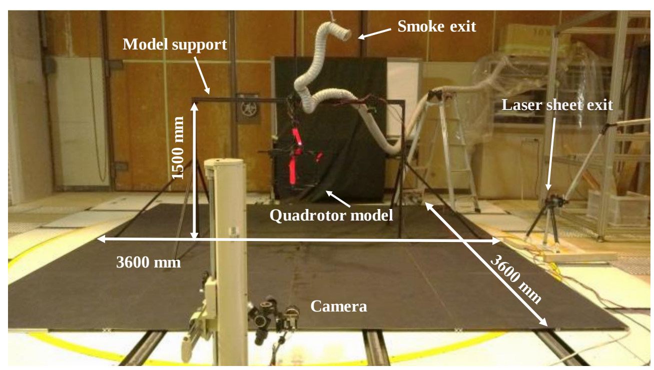

Figure 3. Experimental setup for flow visualizations and PIV measurements.

The visualization planes were set at foul patterns, as shown in Fig. 4. Planes #1 and #2 contain a rotor each and were 3 cm offset from the centers of the rotors. Planes #3 and #4 are at the midpoints of the rotors, implying that there is no rotor at the planes. For the quadcopter configuration, the rotation direction of adjoined rotors differs. Therefore, planes #3 and #4 differ in rotor blade movement near the plane. In plane #3, rotor blades move toward the center of the quadcopter, while in plane #4, they move toward the outer side of the quadcopter. Table 1 summarizes the conditions for rotor measurements. Smoke was generated from the smoke generator and released from the outlet, which was set above the setup. Nd: Yttrium aluminium garnet (YAG) laser was the light source of the laser sheet. The laser illuminated target planes from the side of the quadcopter. The width of the sheet was 2 mm. Figure 5 shows the setup illuminated using a laser sheet. The results of flow visualization and PIV measurements were assembled with pictures of different areas at different moments in the same conditions because the camera viewing area was very small to realize a moderate resolution. Furthermore, moderate density smoke spreads in a narrow area, implying that it could not cover the whole target area simultaneously. Therefore, a linear guides system was used to linearly move the camera position to the target plane, and images were captured in different areas at the same plane. Moreover, PIV vector maps were assembled with each target plane because of the camera view area limitation.

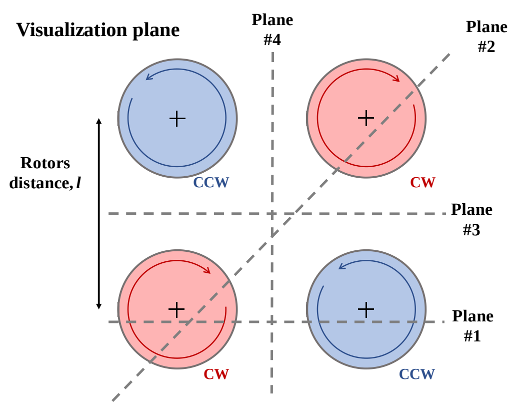

Figure 4. Position of the visualization planes.

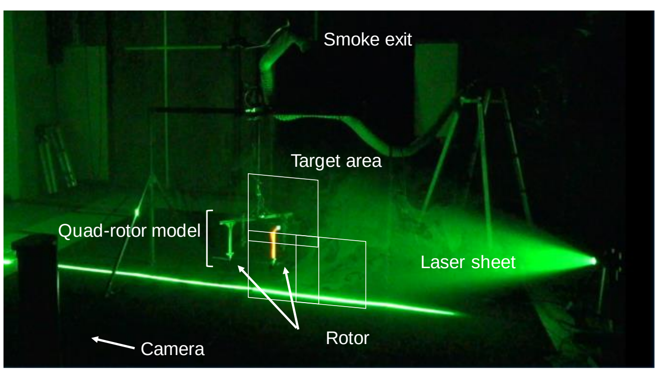

Figure 5. Setup with the laser sheet.

Flow visualization

A flow visualization was conducted to examine the structural characteristics of the quadrotor wake. Pictures were taken from the side by using a 4-megapixel resolution CMOS camera. The frame rate was set at 10 Hz. We recorded pictures of the wake, and selected pictures to present wake features. The pictures were taken over 50 s. To capture the wake structures, the smoke was generated intermittently to adjust the density. Flow visualizations were conducted only for plane #2 in Fig. 4, which is the slice view of two diagonal rotors.

PIV measurements

PIV measurements were conducted to examine the flow direction of the wake at different heights and rotors distances. The frame rate was 10 Hz, and the interval between a pair of pictures to calculate the flow field vector was 400 μs. We measured the vector map of wake 1000 times and averaged them. The seed particle of the smoke was generated using a heat exchanger from fog fluid. Diameter of the seed particle was 1.5 μm. The room used in the experiment was filled with smoke once. After stopping smoke generation, we initiated visualization by uniformly spreading a moderate density of particles in the room.

Table 1. Conditions of flow visualization and PIV measurements.

z/R	Rotors distance	Test conditions	
		Flow visualization plane	PIV plane
4.5	2.7	#2	#1, #2, #3, #4
4.5	2.1	Not conducted	#2
0.5	2.7	#2	#1, #2, #3, #4
0.5	2.1	#2	#2

RESULTS

The flow field of the quadcopter wake was visualized using a laser sheet at plane #2, and PIV measurements were conducted for planes #1–4 at different ground off heights and different distances between the rotors. The visualization images show wakes of the right-side rotor.

Flow visualization

OGE operation with the wider rotor distance. Figure 6 shows the flow visualization result with ground off height of 4.5 *R* and l = 2.7 *R*. The figure shows that the wake collides with the ground plane and spreads to outer side. The wake contains vortex rings near the inner and outer boundaries. The vortex rings merge to the flow while moving down to the ground plane. We could not confirm vortex rings near the ground plane. After reaching the ground plane from the rotors, the wake soared in the upper direction at the center of the body. The soaring flow reached the height of the rotor plane and entered the rotor again. Outside the body, the wake spread in the outer direction. Furthermore, the wake boundary was slightly bent toward the center of the body.

IGE operation with the wider rotor distance. Figure 7 shows the flow visualization result with ground off height of 0.5 R and l = 2.7 R. Here, the wake contains tip vortex rings the same as those in the isolated rotor wake. However, the movement of the rings along the wake flow was asymmetrical to the inner and outer sides of the quadrotor.

The wake is shrunken compared with the wake at $z/R = 4.5$. Therefore, the vortex rings reached the ground plane and spread. Inside the quadrotor, the vortex rings moved in the upper direction with the soaring flow from the wake. The soaring flow passed the height of the rotor plane and width of the flow boundary shrunk. Outside the quadrotor, the vortex rings moved horizontally along the ground plane. The wake between the rotor and ground plane was difficult to observe in the visualized flow with smoke because of the unsteady and fast flow. The flow is generated from the upper side of the rotor shrink as it gets close to the rotor. The right edge of the smoke entrained into the rotor was approximately 2 R away from the rotor shaft at $z/R = 2$.

IGE operation with the closer rotor distance. Figure 8 shows the flow visualization result with the ground off height of 0.5 R and $l = 2.1$ R. Here, the wake contains tip vortexes similar to those in the case of IGE operation with wider rotor distance. The tip vortexes in the rotor wake at the side farther from the center of the quadcopter spread to the outer side of the quadcopter and moved along the ground plane. The tip vortexes at the inner side of the quadrotor soared at the center of the quadrotor. However, the observed vortexes were thinner and the width of soaring flow was smaller than that in the case of the wider rotor distance with IGE. Moreover, smoke entrained into the rotor coming from the upper right side area of the rotor was confirmed.

PIV measurement

The PIV measurement results were expressed using a vector map. The counter color and size of arrow expressed the velocity magnitude of each vector. The evaluation of the exact speed at the measured points needs discussion because flow speed evaluated in the PIV measurements differs from the true speed of the flow. We used the results to examine the flow path, direction, and features of the velocity map.

OGE operation with the wider rotor distance. Figure 9 shows the averaged vector map from PIV measurements with ground off height of 4.5 R and $l = 2.7$ R. The features sketch of the wake is illustrated at bottom part of the figure. For plane #1 in Figs. 9 (a) and (e), the rotor wake is almost symmetrical to the center of the rotor at a height farther from the ground plane. However, at the ground plane, the velocity of the wake outside the quadrotor is faster than that inside. Furthermore, a strong soaring flow was not observed between the right and left rotors, and a weak circulation remained at the blade tip inside the rotor. Moreover, tip vortices were observed at both edges of the wake in moment velocity map as sketched.

For plane #2 in Figs. 9 (b) and (f), the rotor wake was asymmetrical to the center of the rotor. The outer wake velocity was faster than the inner near the ground plane. In addition, the horizontal velocity in the wake vectors moved toward the inside of the quadrotor. Therefore, the wake flow direction slanted toward the inside of the quadrotor. The speed of the wake core region was over 10 m/s. A soaring flow developed at the center of the quadrotor, and reached the height of the rotor plane. The flow entrained the rotor again and formed a circulation flow. In this plane, tip vortexes were confirmed at wake edges in momentum flow images, as sketched in Fig. 9 (f).

For plane #3 in Figs. 9 (c) and (g), soaring flow was confirmed at the center of the quadrotor. The center area was the same for the soaring flows of planes #3 and #4. The plane does not contain rotor; thus, the area under the rotor was not exactly under the rotor center. At this area, the flow emanated from the outside. At midheight between the rotor and ground plane, the flow appeared to move downward. Near the ground plane, a large part of the downwash spread to the outside, and part of the downwash moved toward the soaring flow at the center of the quadrotor. The top end of the soaring flow was near the inside of the rotor blade tip, and a circulation flow was formed, as sketched in Fig. b1(g).

For plane #4 in Figs. 9 (d) and (h), the basic structure of the flow was the same as that in plane #3. Soaring flow and downwash were confirmed. However, velocity of the downwash under the rotor was faster than that in plane #3. Moreover, the amount of flow entering the soaring flow from the downwash was lesser than that in plane #3.

IGE operation with the wider rotor distance. Figure 10 shows the averaged vector map of PIV measurements with ground off height of 0.5 R and $l = 2.7$ R. For plane #1 in Figs. 10 (a) and (e), wake shrinking was observed and the wake spread toward the inside and outside of the quadrotor along the ground plane. A strong circulation was observed at the blade tip near the center of the quadcopter. Moreover, the wake sored between the rotors and entered the rotor again. The flow entering into the rotor disk emanated from the upper parts of the rotor planes, and soaring flow was not confirmed except for the circulation at blade tip. The same as in higher rotor case in Fig. 9 (e), vortex rings were observed at both sides of the wake edges. Vortexes that were formed inside the quadrotor disappeared promptly compared with those formed outside.

Plane #2 in Figs. 10 (b) and (f) contains the center of the quadrotor. At the center of the quadrotor, a strong soaring flow was developed. The flow reached the top support frame. The velocity of the soaring flow was approximately 11m/s. Moreover, a strong circulation was formed similar to that in plane #1. Outside the rotor, the flow entrained in the rotor emanated from the upper area of the rotor, and the wake of the rotor spread along the ground plane. In addition, vortexes were observed at both sides of wake edges, as sketched in Fig. 9(f). The visualized flow of this condition is shown in Fig. 7.

OGE and IGE operation with closer rotor distance. Fig. 11 shows the averaged vector map of PIV measurements at ground off height of 0.5 and 4.5 R and $l = 2.1$ R. For z/R = 4.5 at plane #2 in Figs. 11 (a) and (b), the rotor wake is asymmetrical, the same as that of plane #2 of the wider rotor in Figs. b1 (a) and (e). The rotor wake was pulled to the center of the quadrotor, and the wake flow velocity outside the quadcopter was faster than that inside. Therefore, the vortex sheet was slanted toward the center of the body. The wake flow pulled toward the center merged with the opposite side rotor wake at midheight from the ground plane. At the ground plane, the wake flow moved toward the outside of the quadcopter along the plane. In this condition, a soaring flow was not observed at the center of the quadcopter, although it was observed at the wider rotor distance case. Near the blade tip inside the quadcopter, a small soaring flow area was observed. This rising flow formed circulation around the rotor blade tips at the center of the quadcopter, as sketched in Fig. 11 (b). In this condition, the flow above the rotors moved lower and entered the rotor disk. Therefore, a rising flow was not observed above the rotor height. Blade tip vortexes were confirmed at the wake boundaries.

For z/R = 0.5 at plane #2 in Figs. 11 (c) and (d), the wake was compressed, the same as in the other cases when z/R = 0.5. Outside the quadrotor, the wake spread toward the outside along the ground plane. Inside the quadcopter, the wake reached the ground plane and sored at the center of the quadcopter. we could not determine the exact velocity because the front rotor overlapped the captured image. Nevertheless, the soaring flow speed was approximately 10 m/s at the height of 2 R. At both side edges of the wake, blade tip vortexes were observed. At the inside of the quadcopter, vortexes were transported toward the upper side of the rotor along the soaring flow.

DISUCUSSIONS

Comparison between isolated rotor and quadrotor

The wake structure of the quadrotor in our experiments is different from the isolated rotor wake shown by Lee, Leishman, and Ramasamy [17]. The wake of the isolated rotor is symmetrical to the center of the rotor, while the wake of a rotor of the quadrotor is asymmetrical to the rotor shaft and interfered with the other three rotor wakes. Outside the quadcopter, the wake spread toward the outside. However, the wake flow inside the quadcopter moved toward the center at the ground plane and resulted in a rising flow. A soaring flow did not appear in the wake of the isolated rotor. Thus, the occurrence of the soaring flow and asymmetry of rotor wake to rotor shaft axis are differences of the quadrotor wake to isolated rotor wake.

Comparison between OGE and IGE with the wider rotor distance.

The comparison of the ground heights with a rotor distance of l = 2.7 R in Figs. 9 and 10 shows that the soaring flows at the center of the quadcopter are different. At OGE operation, the soaring flow is weak and the velocity is approximately 3 m/s; the flow reaches a height of the rotor plane. In contrast, at IGE operation, the soaring flow is strong and velocity is approximately 11 m/s; the flow passes the rotor plane and moves to top of the target view area. Therefore, a soaring flow develops with the lowering height of the rotor planes at the wider rotor distance. Moreover, the wake flow of the rotor spreading toward the outside of the quadcopter moved horizontally at z/R = 4.5. However, for z/R =0.5, wake flow of the rotor spreading toward the outside soared from the ground plane at planes #3 and #4. Thus, at IGE operations, a blowing flow to soar was developed from the rotors clearance and the rotors edge outside of the quadcopter.

Comparison between OGE and IGE with the closer rotor

The comparison of the ground off heights with rotors distance l = 2.1 R in Figs. 11 (a) to (d) shows that the soaring flow development at the center of the quadcopter are different. The basic feature is the same as that of the wider rotor distance operations. At z/R = 4.5, soaring flow is not observed. As the rotor got close to the ground plane, a soaring flow appeared at the center of the quadcopter.

Comparison of rotors distance OGE operations

The comparison of the rotors distances at OGE operations in Figs. 9, 11 (a), and 11 (b) shows that the soaring flow at the center of quadrotor is different. In case of a small distance between rotors, a soaring flow was not observed. In contrast, soaring flow appeared for wide rotor distances. Therefore, the rising flow disappeared with closing rotor distance. We presumed that the closing rotor distance eliminates rotor clearance at the height of the rotor plane for the passing flow. Therefore, it is easier for the flow to spread outside than to converge in the center of the quadcopter, and the soaring flow disappears.

Comparison of rotors distance IGE operations

The comparison of the rotors distances at IGE operations in Figs. 10, 11 (c), and 11 (d) shows that the basic characteristics of the flow structure are similar. Soaring flow develops at the center of the quadcopter at both rotor distances. However, velocity of the rising flow with l = 2.7 R is faster than that with l = 2.1 R. The velocities with l = 2.7 and 2.1 R were 11 and 10 m/s, respectively. The width of the rising flow with the close rotor distance is smaller than that of the flow with the wide rotor distance. The closing rotor distance seems to impede the development of soaring flow.

Effect of the soaring flow.

In quadcopters, the body is located at the center of four rotors. Therefore, the body seems to be pushed by the soaring flow refracting from the ground plane. We speculate that this mechanism reinforces the thrust increase in the ground effect. Thus, it is expected that changing the distance between the rotors will affect rotor thrust in the ground effect. Furthermore, a blockage plate between rotors can eliminate soaring flow. The dependency of thrust change in the ground effect on the rotor distance can be weakened. To examine the effect of soaring flow in the thrust in the ground effect, we must examine the relation of thrust and rotor distances. In addition, a quadcopter controller contains the atmospheric pressure sensor, which is used as height sensor in a number of cases. The effect of unstable soaring flow on the pressure sensor vibration is a topic of concern. For stable take-off and landing of multicopter UAVs, more studies are required on the wake of the multicopters.

CONCLUSIONS

To examine the structure of wake of the quadrotor experimentally, we conducted flow visualization and PIV measurement at different ground off heights and different rotor distances. We draw the following conclusions from this study.

1) In the quadcopter wake, a soaring flow reflected from the ground plane develops at the center of the quadcopter at a height in the ground effect. The velocity of the soaring flow depends on the rotor clearance at the center of the quadcopter. With closing rotor distance, the wake is weakened. At a rotor distance of 2 *R*, the soaring flow does not appear.

2) The rotor wake of the quadcopter is asymmetrical to rotor shaft axis, which is not as similar as that of the isolated rotor wake. The wake is pulled to the center of the quadcopter. Thus, the rotor wake is slanted toward the inside of the quadcopter. The vertical speed of the wake outside the quadcopter is faster than the speed inside.

3) The velocity and direction of the spreading flow from the quadcopter at the ground plane are different in the visualization planes. The spreading flow has a directional difference on the velocity. The speed depends on whether the plane contains the rotor wake.

We experimentally analyzed the wake structures of the quadcopter configuration and verified the existence of the soaring flow, which is unique for the wake of plural rotor configuration. The flow can affect the stability of the body posture in the ground effect. Moreover, the effect on thrust increase with the ground effect is a topic for concern. To realize stable take-off and landing, further studies are required with experiments and numerical analysis validations.

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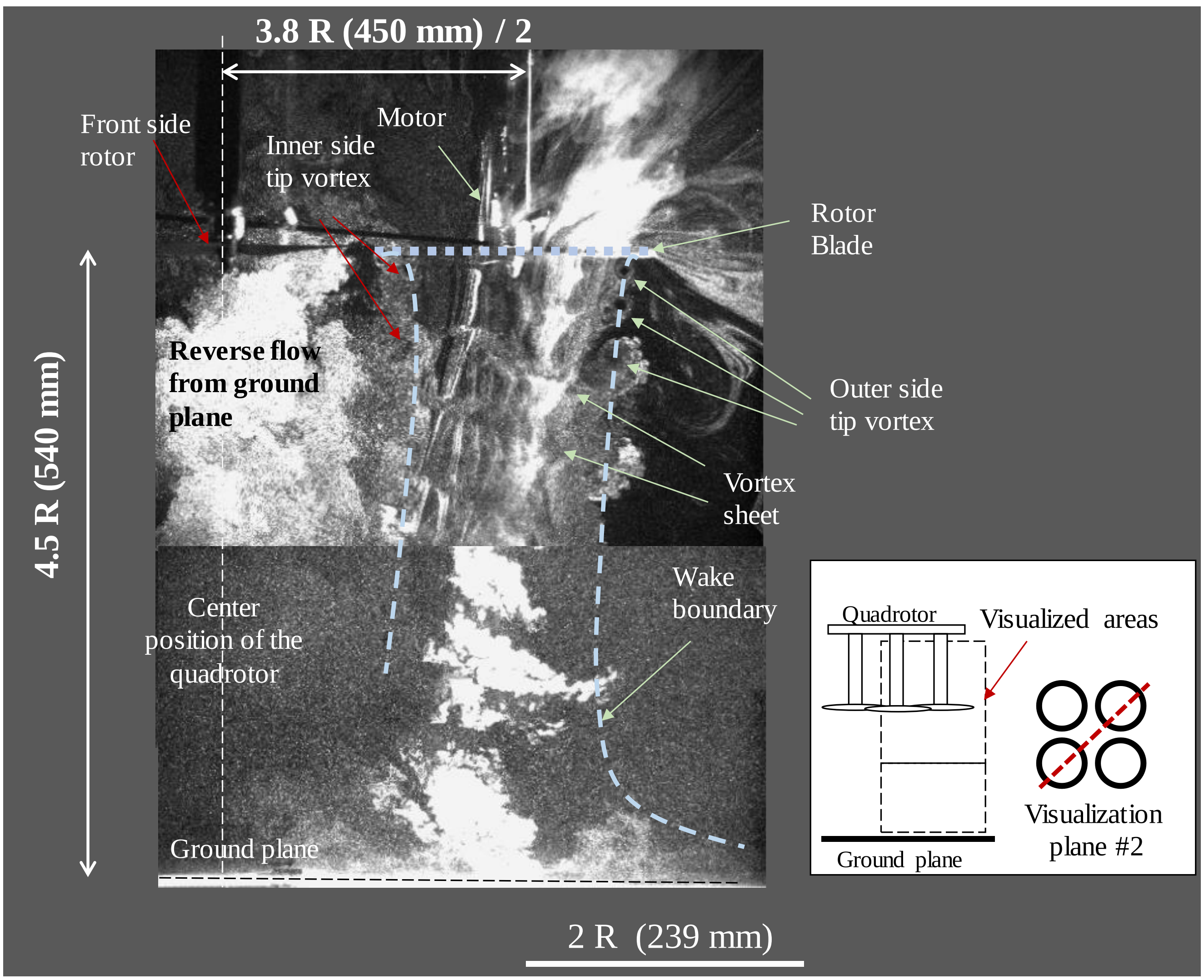

Figure 6 Visualized rotor wake of IGE operations at close rotor distances.

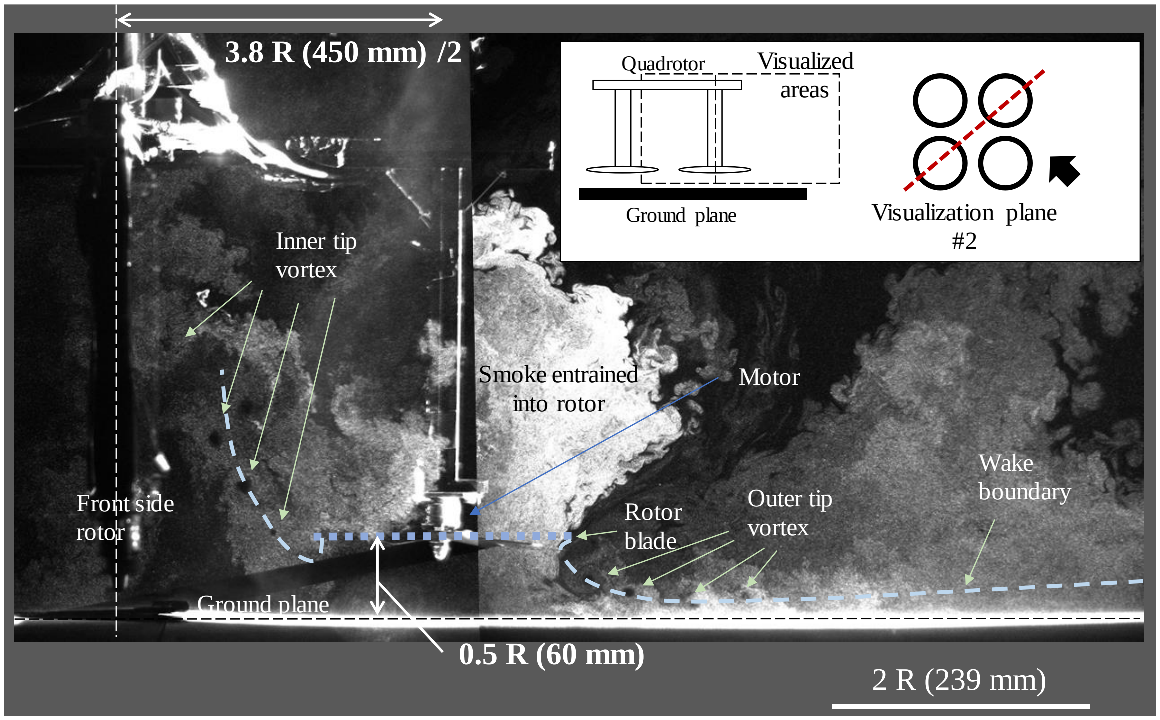

Figure 7. Visualized rotor wake of IGE operation at wide rotor distances.

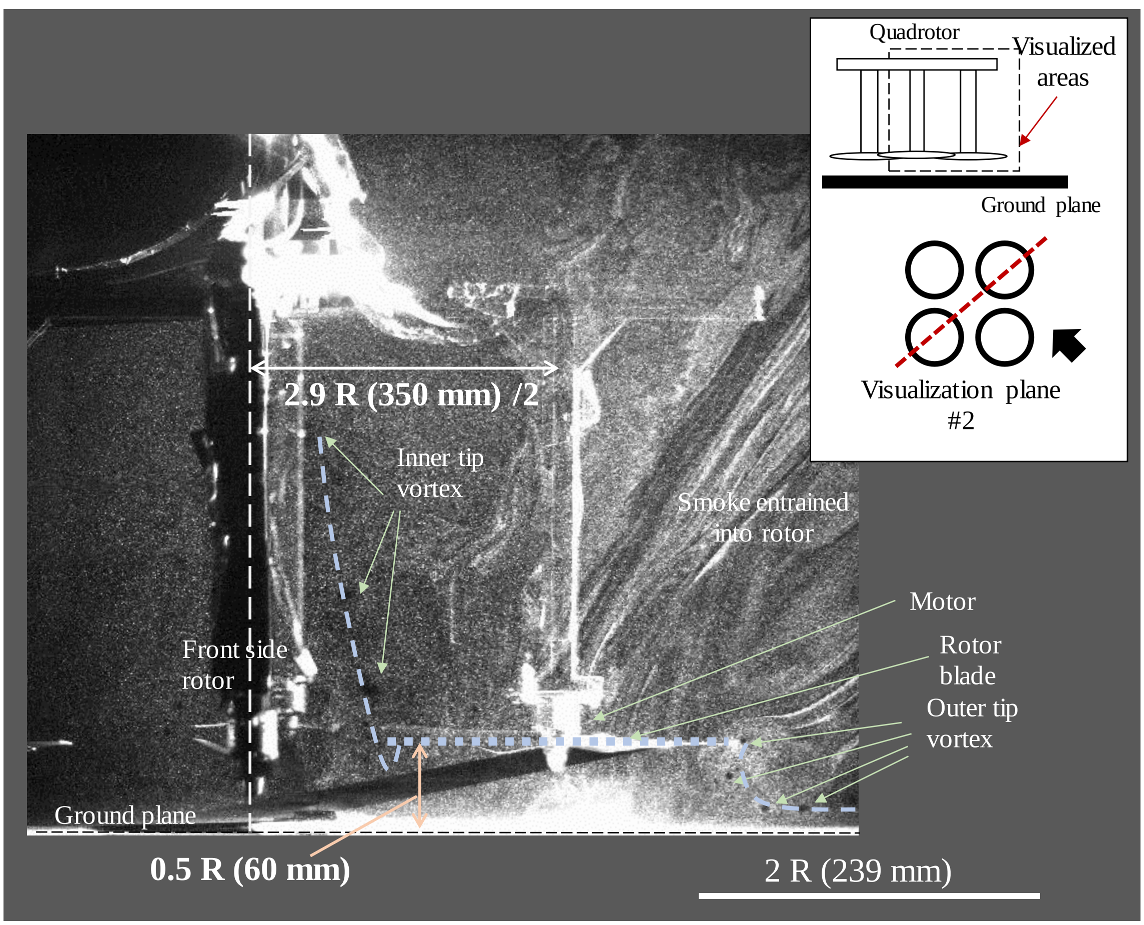

Figure 8 Visualized rotor wake of IGE operation at close rotor distances.

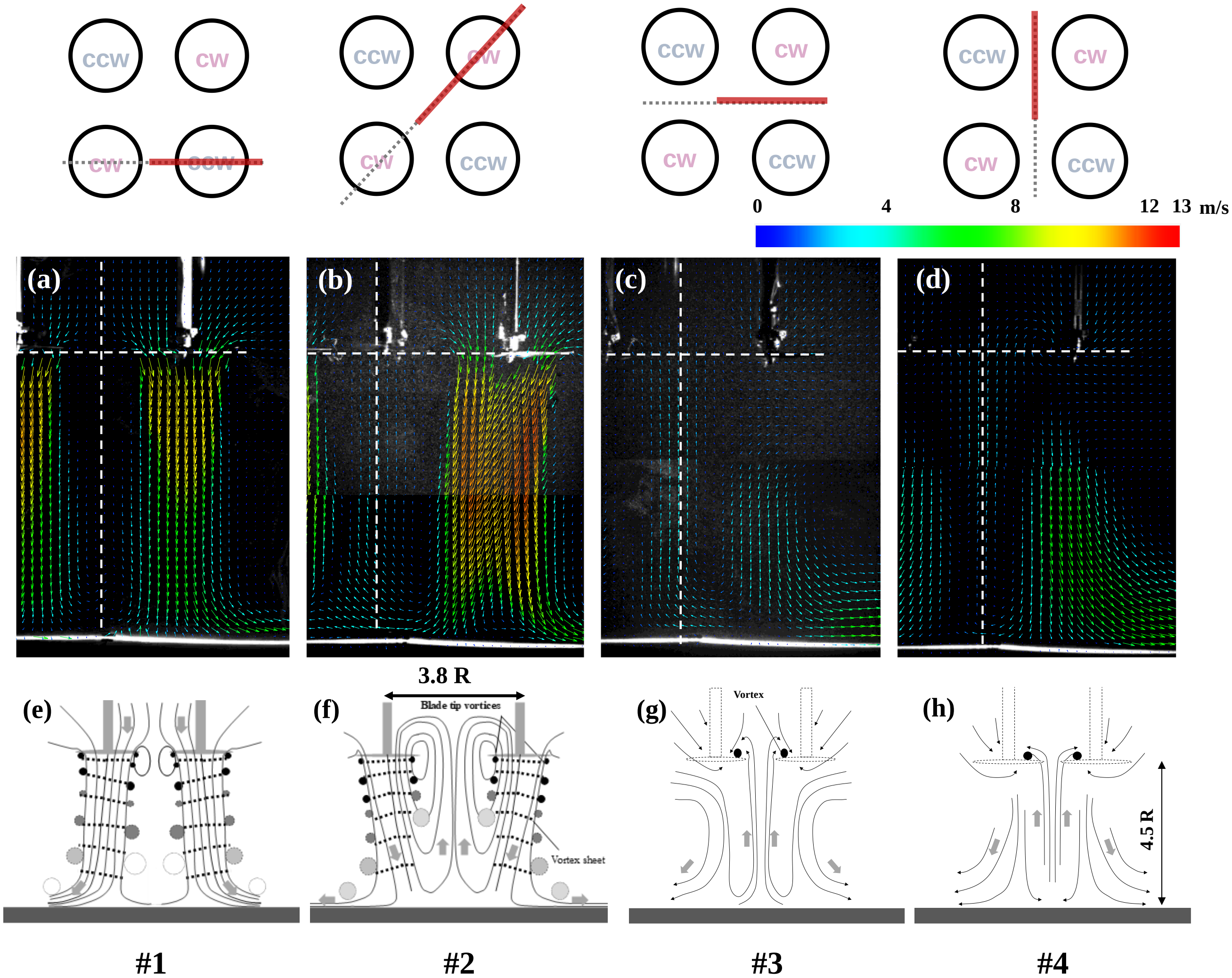

Figure 9 Wake of OGE operation at wide rotor distances.

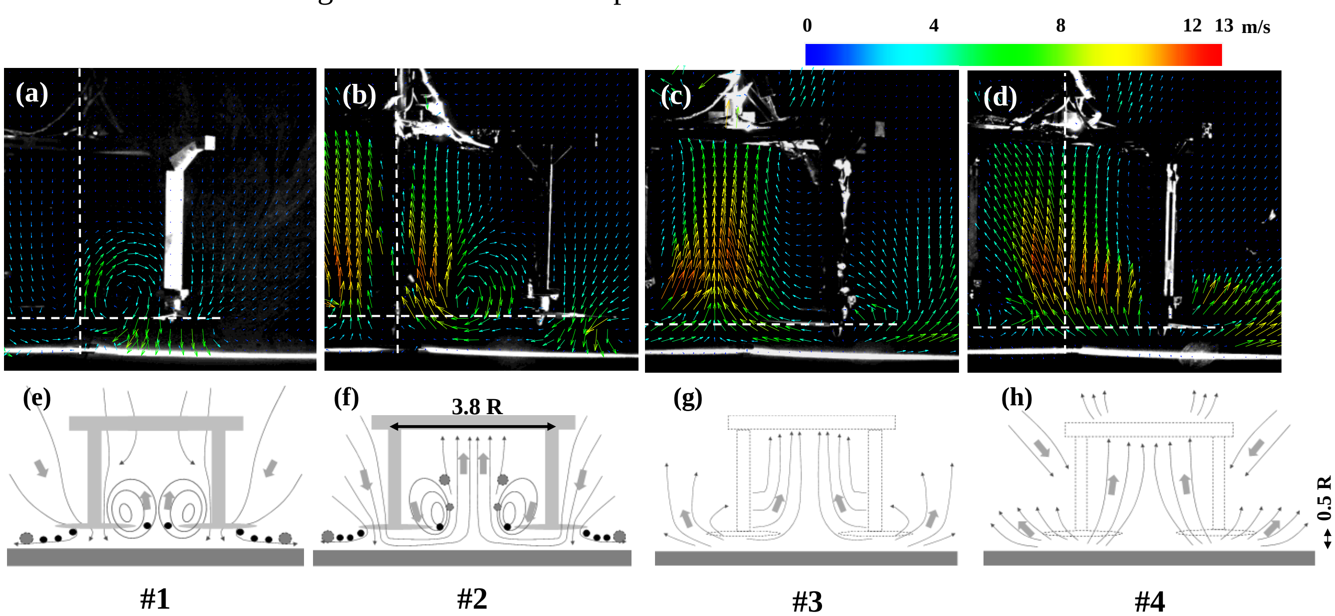

Fig. 10 Wake of IGE operation at wide rotor distances.

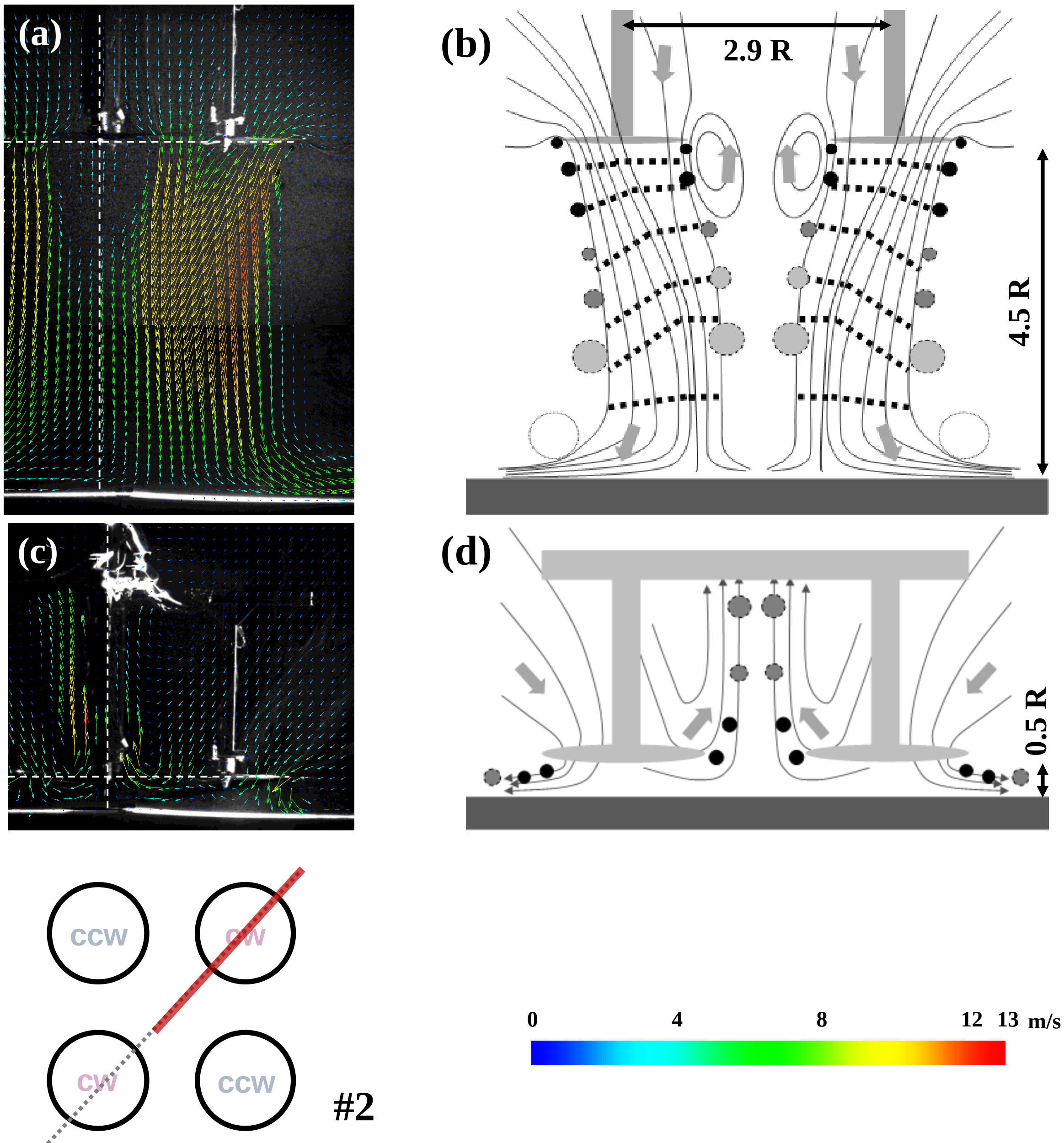

Figure 11 Wake of OGE and IGE operations with close rotor distances.