GROUND EFFECT OF A QUADCOPTER FLYING ABOVE INCLINED PLANE

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Abstract

Multicopters used for facility inspection are often required to fly very close to structures. However, it is known that the behavior of multicopters in the vicinity of structures can be unstable. In this study, the ground effect when there is an inclined ground plane below the quadcopter was investigated experimentally and numerically. The results show that imbalanced aerodynamic forces which can disturb the flight are generated by different mechanisms depending on the propeller configuration and flight altitude: when flying near the inclined plane with the thrust force of the four rotors maintained constant, the torque acting on the rotors changes depending on the inclination angle of the ground plane. The change in torque is influenced not only by the distance between the rotor and the inclined plane, but also by the distance between neighboring rotors. It was suggested that an imbalance of yawing moments may occur in the quadcopter, which makes flight unstable, depending on the azimuthal angle of the quadcopter with respect to the inclined plane.

1. NOTATION

Symbols

D	Rotor diameter, m
d	Rotor tip-to-tip distance between neighboring rotors, m
h	Altitude of quadcopter (Altitude of quadcopter center from the ground plane), m
hr	Altitude of rotor center from the ground plane, m
ϕ	Azimuthal angle of quadcopter, degree
θ	Incline angle of ground plane, degree

2. INTRODUCTION

In recent years, research and development on multicopters of various sizes has been carried out widely, and it is expected that multicopters will be applied to a wide range of industries. However, practical issues for multicopters still include improving aerodynamic performance, which leads to longer flight times and higher payloads, and improving flight safety. Small unmanned multicopters are sometimes used for inspection applications with in-close flight of buildings and structures. Medium and large manned multicopters as advanced air mobilities (AAM), will also be operated at heliports in a variety of locations, including urban areas in near future. Thus, multicopters is and will be often operated in different situations from conventional single-rotor helicopters. In addition, considering that multicopters have multiple rotors, it is expected that the aerodynamic characteristics may often be beyond the knowledge of conventional single-rotor helicopters. Since personal electric manned multicopters are not capable of flying long distances, they are expected to be used for short distance travel, and for convenience, operations with frequent take-offs and landings in urban areas are expected. Therefore, to understand the aerodynamic characteristics at low altitude flight is important to improve the flight safety of small multicopters for inspections that fly close to structures, as well as for personal manned multicopters in urban areas. Previously, the authors have studied the aerodynamic characteristics of multicopters flying low-altitude above horizontal ground, which are reported as Refs.1 and 2. Maintaining a constant thrust, the axial torque decreases as the altitude decreases and the distance between the ground and the rotor becomes closer. When the distance between the rotors is increased, the relationship between the decrease in axial torque and flight altitude becomes closer to that of the single-rotor case. On the other hand, when the distance between the rotors is closer, the aerodynamic interference becomes stronger, and the ground effect appears at higher altitudes than in the single rotor case, which are presented in Refs. 3 and 4. In this study, the case of a multicopter flying at low altitude over an inclined plane was investigated through experiments and numerical analyses. This is a hypothetical situation that might be encountered by a small multicopter flying near a structure for inspection or a personal manned multicopter used in an urban area.

3. EXPERIMENTAL METHOD

3.1. Test facility

Figure 1 shows the quad-rotor hovering test stand. The rotor diameter, D is 240 mm, and the rotor blades and DC motors were taken from DJI Phantom 4. The locations of the rotors can be varied along the rotor arms. Each rotor is supported by a 6-component load cell. The force and moment capacities of the load cell are 30 N and 0.5 Nm respectively. Each rotor revolution speed is detected by ESCs. Signals from the load cells and ESCs are sent to a controller. The controller provides for constant thrust or speed of each rotor and the load cell output and revolution speed are transmitted to and recorded by a PC.

The hovering test stand were located at the center of a ground model for the ground effect tests, as can be seen in Figure 2. The ground inclination angle can be varied between 0°-30°.

Configurations of the quad-copter above the inclined plane were determined using the rotor tip-to-tip distance between the neighboring rotors, d, the altitude of the quadcopter, h, the incline angle of ground plane, θ, and the azimuthal angle of the quadcopter to the inclined plane, ϕ, which can be seen in Figure 3. The azimuthal angle of the quadcopter is determined as follows: the rotors 1 and 2 are at close to the inclined plane (lower altitude) and the rotors 3 and 4 are at far

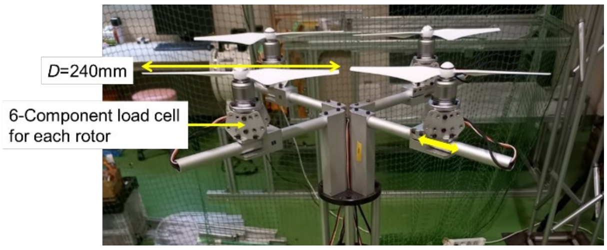


Figure 1: Hovering test stand

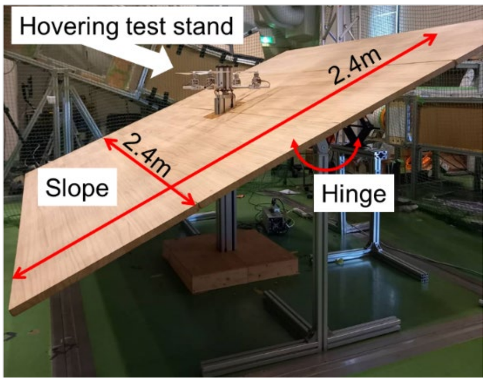


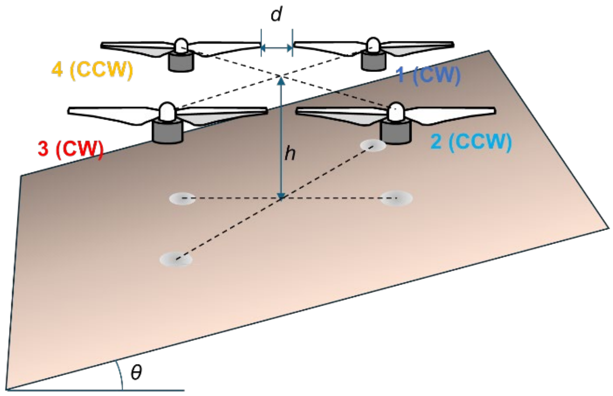
Figure 2: Overview of ground effect test facilty. Hovering test stand and slope.

from the inclined plane (higher altitude) when ϕ = 0°. The rotor 1 is at the closest to the inclined wall and the rotor 3 is at the furthest when ϕ =45°. The rotational direction of each rotor is also presented and clockwise (CW) and counterclockwise (CCW) rotors are arranged in an alternative arrangement. Experiments were carried out for eight kinds of configuration as shown in Table 1.

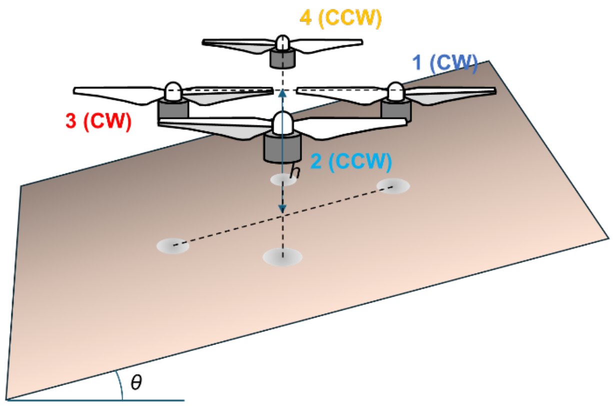
All experiments were carried out with the thrust value of each rotor of 3.38 N. By the controller of the test stand, the revolution speed of each rotor was adjusted to maintain the thrust value. Therefore, the thrust coefficients of four rotors are not identical when the rotors are affected by the inclined plane.

4. NUMERICAL METHOD

To simulate and examine flow patterns at the same condition with experiments, 3-D unsteady numerical simulations were carried out. The numerical simulations were carried out using rFlow3D, which was developed for aerodynamic analysis of rotorcraft at JAXA and the details are presented in Ref. 5. These numerical methods were validated for the multicopters in Refs. 6 and 7. A three-dimensional



a) ϕ = 0°



b) ϕ = 45°

Figure 3: Configuration of quad-copter above inclined plane.

Table 1 Configuration of experiments

Configuration	*d/D*	*h/D*	ϕ
1	0.187	1.0	0 °
2	0.187	2.0	0 °
3	0.71	1.0	0 °
4	0.71	2.0	0 °
5	0.187	1.0	45 °
6	0.187	2.0	45 °
7	0.71	1.0	45 °
8	0.71	2.0	45 °

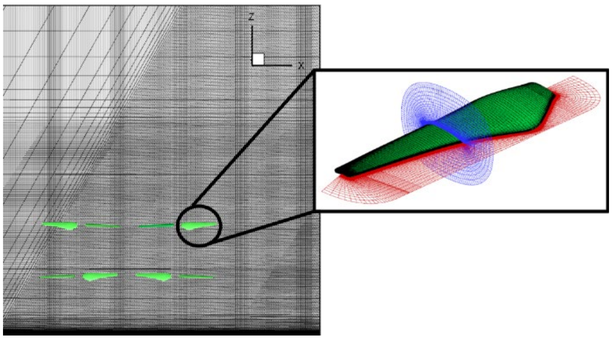


Figure 4: Overlap grid system

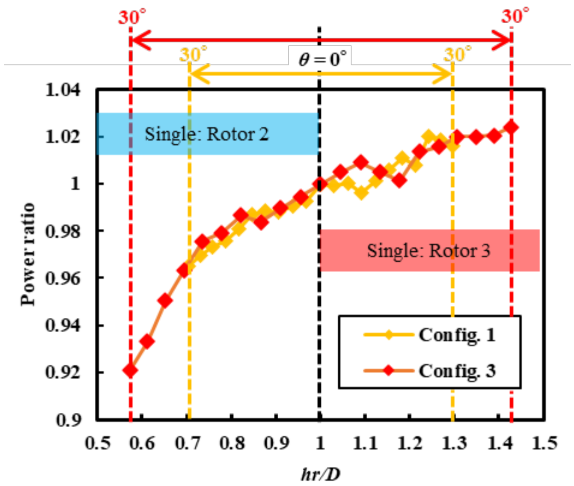


Figure 5: Change of rotor power of single rotor in the inclined ground effect.

moving overlapping grid technique is used in rFlow3D as shown in Figure 4, in which the blade grids move in an outer background grid. Eight blocks of the blades, in which 143×151×71 points of grid nodes in blade-span × chord × normal directions, are used. As a block of the background field (X=48 m, Y=48 m, Z(altitude) =24 m), 449×449×333 points of grid nodes are placed in X (length) × Y (width) × Z (height) directions. The bottom of the background grid was treated as a nonslip wall to simulate the ground.

5. EXPERIMENTAL MEASUREMENT

5.1. Single rotor above inclined plane

By cutting-off the power supplies to three rotors on the test stand with the configurations 1 (*d/D*=0.187) and 3 (*d/D*=0.71), where ϕ = 0°and *h/D*=1.0, aerodynamic power was measured for various θ as the single rotor case.

Figure 5 shows the change in the rotor power in the inclined ground effect as functions height from the

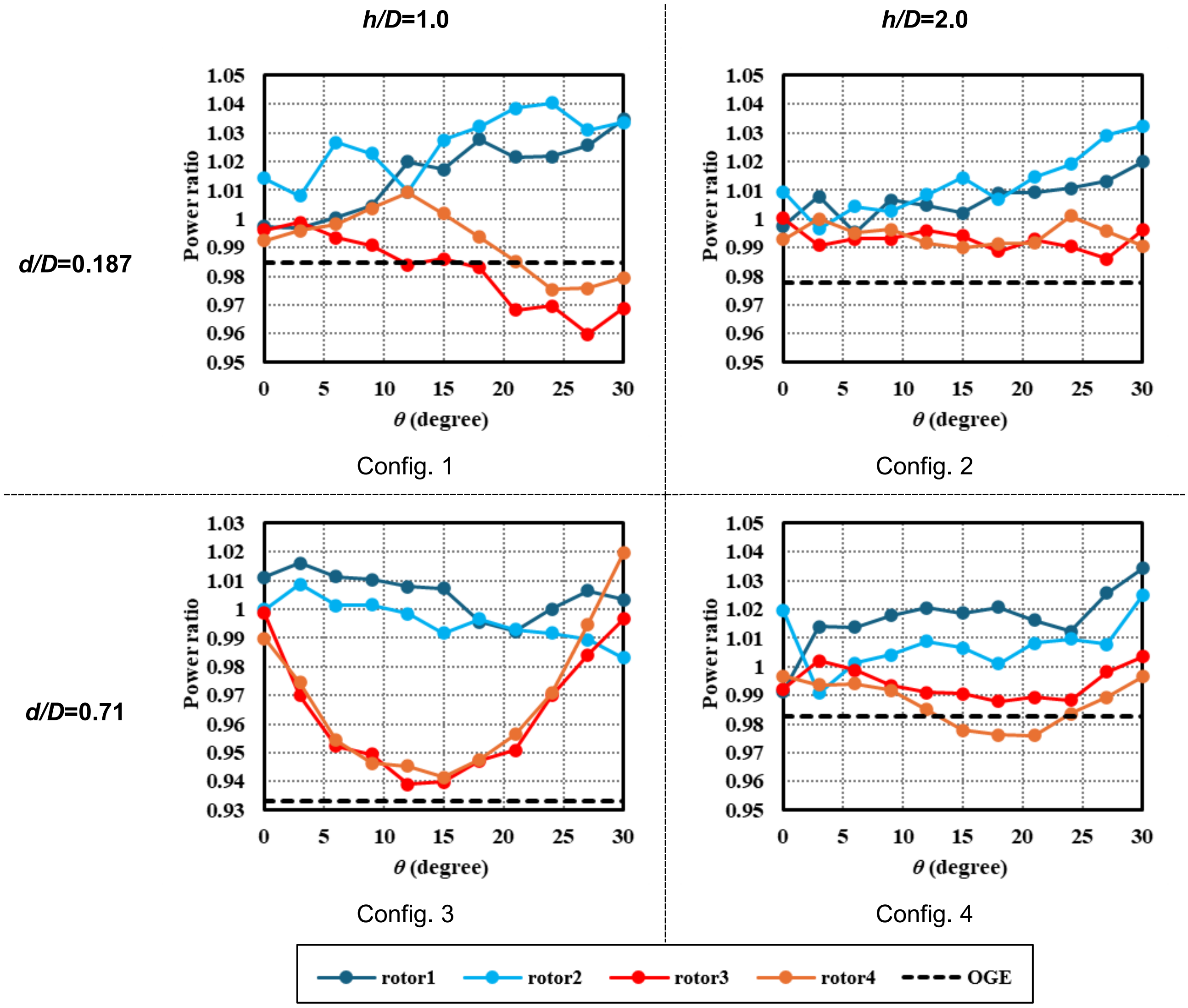


Figure 6: Change of rotor power ratios of quadcopter in the inclined ground effect. (ϕ =0°)

ground to the rotor center, *hr/D*. The results suggest that the ground effect appears as the rotor power decrease due to the altitude, *hr/D,* decrease. This trend is identical to the well-known ground effect above the horizontal ground. He and Leang investigated the characteristics of ground effects for various fixed rotors and reported as Ref. 8. In this study, the ground effect disappeared around *hr/D* = 1 for all kinds of propellers. The present results show that, on the other hand, the rotor power still changes clearly even with *hr/D*>1.5, which suggests the influence of the ground plane inclination.

5.2. Quadcopter above inclined plane

Four kinds of configurations, the case 1-4, are examined with the azimuthal angle of the quadcopter ϕ =0° and the results are shown in Figure 6 as changes in power ratio with regard to θ. In the configurations 1 and 2, the rotor-tip-to-tip distance between neighboring rotors are shorter than those in the configurations 3 and 4. The altitude of the quadcopter in the configurations 1 and 3 are lower than those in the configurations 2 and 4. The values in vertical axes of plots in Figure 6 are the power ratio, which are rotor power values normalized by the mean values of four rotors at θ =0°. Although we can see differences in the values of power ratio between four rotors at θ = 0°, these can be due to slight differences in the shape of each blade and strains during rotation. Comparing the results, the rotor-tip-to-tip distance between neighboring rotors affects the trend of change in the power ratio with regard to θ, while the altitude affects the amount of change in the power ratio with regard to θ. The power ratios of the rotors 1 and 2 increase while

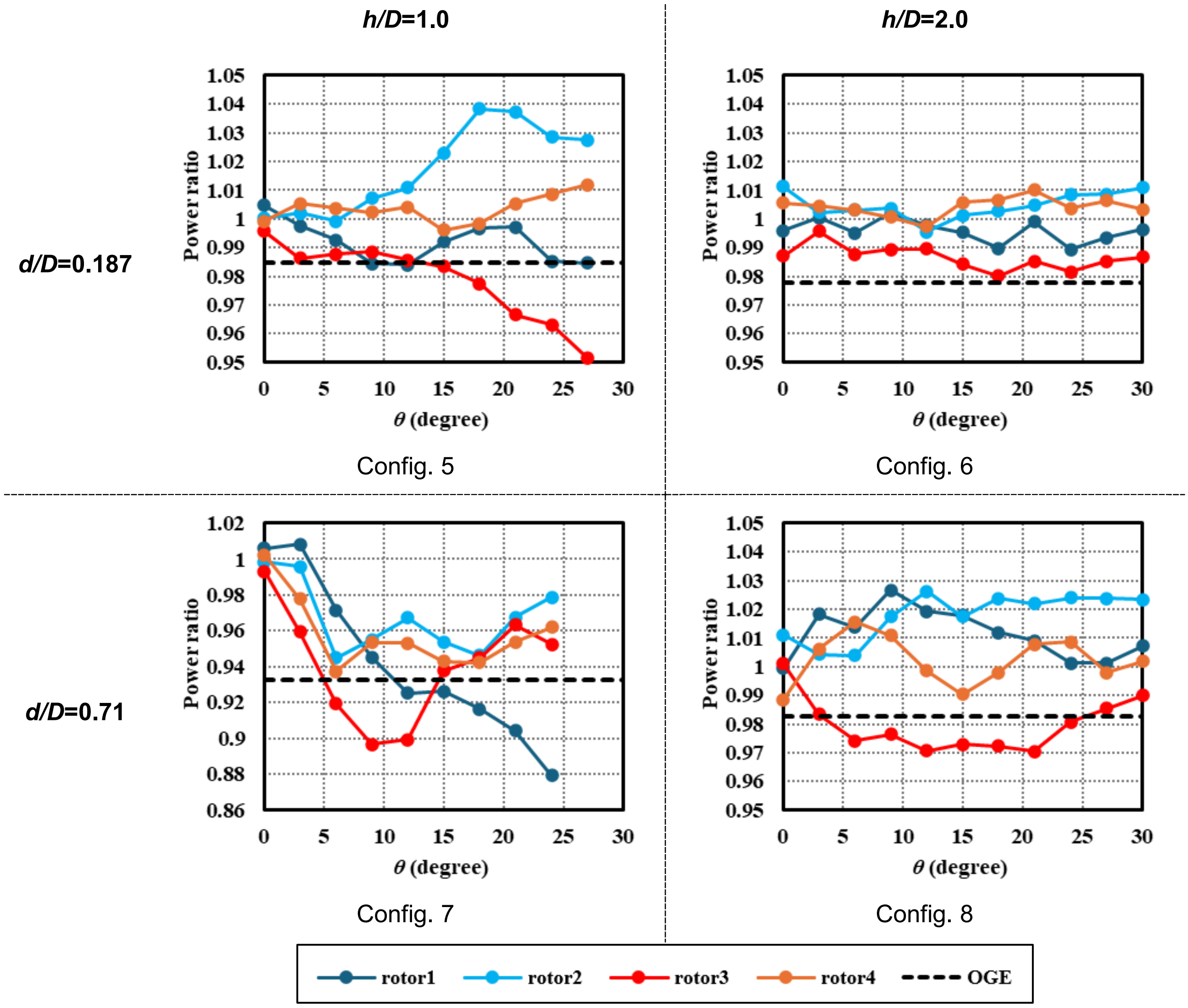
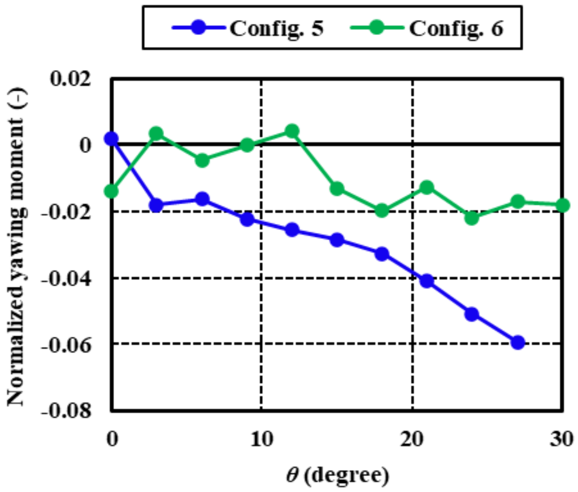


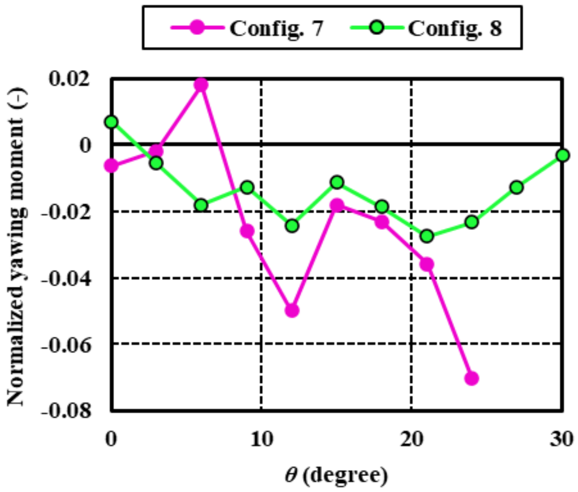
Figure 7: Change of rotor power ratios of quadcopter in the inclined ground effect. (ϕ =45°)

the power ratios of the rotors 3 and 4 decrease as θ increases for the cases of the configurations 1 and 2, which are presented as top two panels in Figure 6. As mentioned above, the power decrease as the rotor height from the ground plane, *hr/D* decrease for the single rotor. However, the results in Figure 6 show that the power of the rotors 1 and 2 increase as *hr/D* decrease. This suggests that the aerodynamic interferences between rotors and inclined ground plane increases aerodynamic loss on the rotors at near side to the inclined ground plane while decrease at far side. Comparing the differences in the power ratios between rotors at the near and far sides, the difference is larger with the configuration 1 than with the configuration2, which corresponds to a tendency for the ground effect to weaken with increasing altitude.

The changes in the power ratio are somewhat complicated, for cases with the configurations 3 and 4, which rotor-tip-to-tip distance between neighboring rotors is larger than those in the configurations 1 and 2. The power ratios of the rotors 1 and 2 slightly decreases for the configuration 3 while increase in the configuration 4. The amount of change is small, but tendency is contrary. On the other hand, the power ratios of rotors 3 and 4 change non-monotonically. The power ratios decrease and become minimum until θ = 15°. When θ increases further, the power ratios of the rotors 3 and 4 turn to increase, and finally become comparable to or larger than those of the rotor 1 and 2 at θ =30°. In the configuration 4, the power ratios of the rotors 3 and 4 decrease up to θ =20°, and turn to increase above θ =20°, although the amount of the change are smaller than those in the



(a) *h/D*=1.0



(b) *h/D*=2.0

Figure 8: Normalised yawing moment of quadcopter versus angle of inclination of the ground plane. (ϕ =45°)

configuration 3. This tendency corresponds to the suppression of the ground effects with increasing the altitude of the quadcopter.

Four kinds of configurations 5-8 are examined with the azimuthal angle of the quadcopter ϕ =45° and the results are shown in Figure 7 as changes in power ratio with regard to changes in θ. In these configurations, the rotor 1 is closest to the inclined ground plane and the rotor 3 is furthest away.

For the configuration 5, the power change with θ of the rotor 3 is the largest and that of the rotor 1 is the smallest. As mentioned above, the ground effect decreases the power consumption with decreasing altitude. However, it is unexpected that the ground effect is most significant at rotor 3, which is at furthest from the inclined plane and at the highest among the four rotors. In particular, for large θ, the power is clearly lower than for rotor 1, which is closest to the inclined plane. In addition, it should be noted that rotors 2 and 4 show an increase in power as θ changes, even though the altitude from the inclined plane does not change as θ changes. These results clarify the dominant effect of aerodynamic interference due to multiple rotors being adjacent to each other. In configuration 6, the change in power with regard to changes in θ is smaller, which is considered to be due to the increased altitude. However, the ground effect, decrease of the power in other words, is most significant at rotor 3, as for the configuration 5.

For the configuration 7, in which the rotor-tip-to-tip distance is larger than the configuration 5, the ground effect is most significant in the rotor 3 under conditions with small θ, and the power is similarly reduced in the other rotors 1, 2 and 4. However, when θ is greater than 15°, the ground effect becomes most significant in the rotor 1, and the rotor power begins to increase in other rotors. In configuration 8, the change in power with respect to changes in θ is smaller, which is considered to be due to the increased the altitude.

Figure 8 shows normalized yawing moment acting on the quadcopter. The yawing moment is normalized by the mean torque value of the 4 rotors. Results show that, the absolute value and variation of the yawing moment is larger when the altitude is small. The yawing moment linearly decrease for the configurations 5 and 6. In Configurations 7 and 8, yawing moment changes are complicated, including decreases and increases.

6. NUMERICAL RESULT

Experimental results confirm that the characteristics of the inclined ground effect differ in many respects from those of the horizontal ground effect. In this study, numerical simulations were carried out for several conditions to understand flow physics of the inclined ground effect. The numerical simulations were carried out for 6 conditions, which were θ = 15° and θ = 30° with the configurations 1 and 3, θ = 30° with the configuration 2 and θ =15° with the configuration 4.

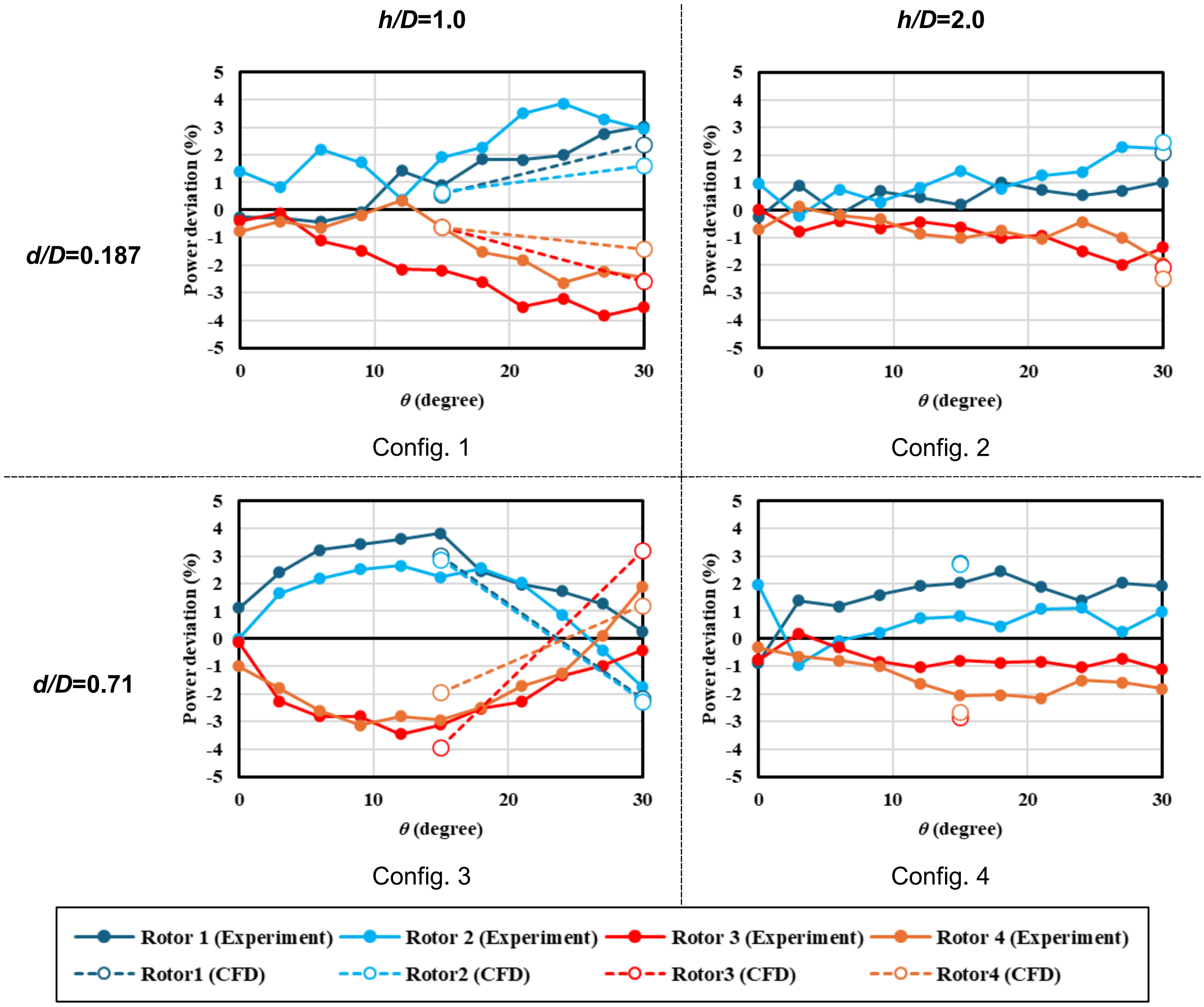
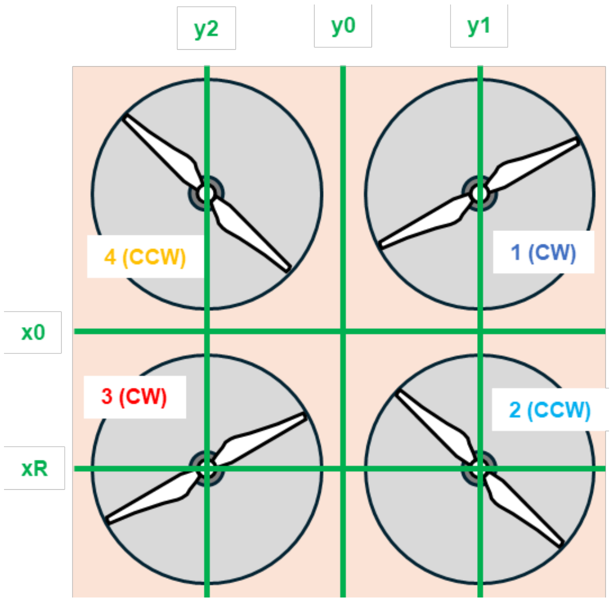


Figure 9: Comparison of power deviation among 4 rotors between experimetns and numerical simulation

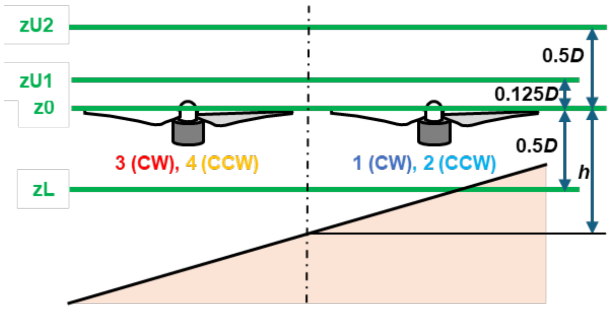
Figure 9 shows the power deviations among rotors 1-4 as functions of θ. Numerical results are plotted as well as experimental results. For the configuration 1, the power of rotors 1 and 2 increases as θ increases, while the power of the rotors 3 and 4 decrease. In the case of configuration 3, the numerical results clearly show that the power of rotors 1 and 2 is greater than that of rotors 3 and 4 at θ = 15°, but this relationship is reversed at θ = 30°. For configurations 2 and 4, the numerical results also agree with the experimental results in terms of values and quantitative relationships. According to these figures, it is confirmed that the numerical simulations successfully capture the characteristics of the inclined ground effect quantitatively.

Flow patters are visualized by the vertical velocity distributions in nine cross sections, which are shown in Figure 10.

Figure 11 shows flow patterns in the configuration 1 and θ =15°. In cross section x0 through the center of the quadcopter, there is a widespread region of upward flow with positive velocities, while in cross section xR through the center of the rotor, the rotor-induced downward flow is most noticeable. In cross section zL below the rotor, the flow pattern is asymmetrically distorted due to the inclined ground plane. It is also remarkable for a narrow positive velocity region distributed vertically and horizontally in a criss-cross pattern through gaps in the rotor wake flows with four circular negative velocities. In the cross section z0 through the rotational plane of the rotors, there are downward induced flow can be seen in the rotational disks. The upward flow region takes place horizontally through the gap between four rotors, which



(a) Top view



(b) Side view

Figure 10: Locations of visualized cross sections. Flow patterns are visualized on 9 cross sections (x0, xR, y0, y1,y2, z0, zL, zU1 and zU2)

is along the cross section x0. The upward flow is enhanced at the center of the quadcopter and to the right of the aircraft, in the vicinity of the inclined ground surface. This upward flow region spread to the cross section zU1 and zU2. According to flow patterns in the cross sections y0, y1, and y2, it is found that the upward flow region is formed resulting of the rotor wake flows impingement on the ground plane. Actually, it was already reported by authors in Ref. 2, that the upward flow region forms symmetrically through the gaps of the four rotors. According to the present result, it is found that the upward flow is enhanced along the inclination of the ground plane when the ground plane is inclined. On the other hand, the upward flow is relatively suppressed, along the direction of the constant height of the inclined ground plane. In summary, an upward flow region is formed between the four rotor wake flows of the quadcopter and is enhanced in the direction along the inclination of the ground plane. Furthermore, an intense upward flow is formed on the upper side of the slope, which is on the right side of the quadcopter in the z0 cross sectional view in Figure 11, resulting in a larger power consumption of rotors 1 and 2 compared to rotors 3 and 4 because this rolled-up flow is re-introduced into the rotor and forms a recirculating flow, hence increasing the amount of ineffective work of the rotor.

Influence of the inclination angle of the ground plane can be discussed by comparing flow patterns between Figure 11 and Figure 12. The inclination angles are 15 and 30 degrees, respectively. The upward flow region can be seen in the cross sections x0 and z0 in both Figure 11 and Figure 12. The upward flow region on the right of the quadcopter in the z0 cross-section appears with higher velocity in Figure 12 than Figure 11 due to higher degree of the ground plane inclination. This suggests that the recirculation flow and losses are larger with the ground plane inclination angle of 30° than those with 15°. As a result, the difference in the deviation of the rotor power increases as θ increases, as shown in Figure 9.

Influence of the altitude of the quadcopter can be discussed by comparing flow patterns between Figure 11 and Figure 13. In the cross section x0, there can be seen the upward flow region on the lower right side of the quadcopter. In Figure 13, however, the area of the upward flow region is smaller than that in Figure 11. It is found that the influence of the upward flow and recirculation loss becomes smaller in Figure 13 than in Figure 11 because of the higher altitude.

The flow pattern for a larger rotor-tip-to-tip distance is shown in Figure 14. The influence of the rotor-tip-to-tip distance can be discussed by comparing with Figure 11. In the x0 cross section, the upward flow region is larger in Figure 13 than that in Figure 11. In addition, a portion of the upward flow region also appears

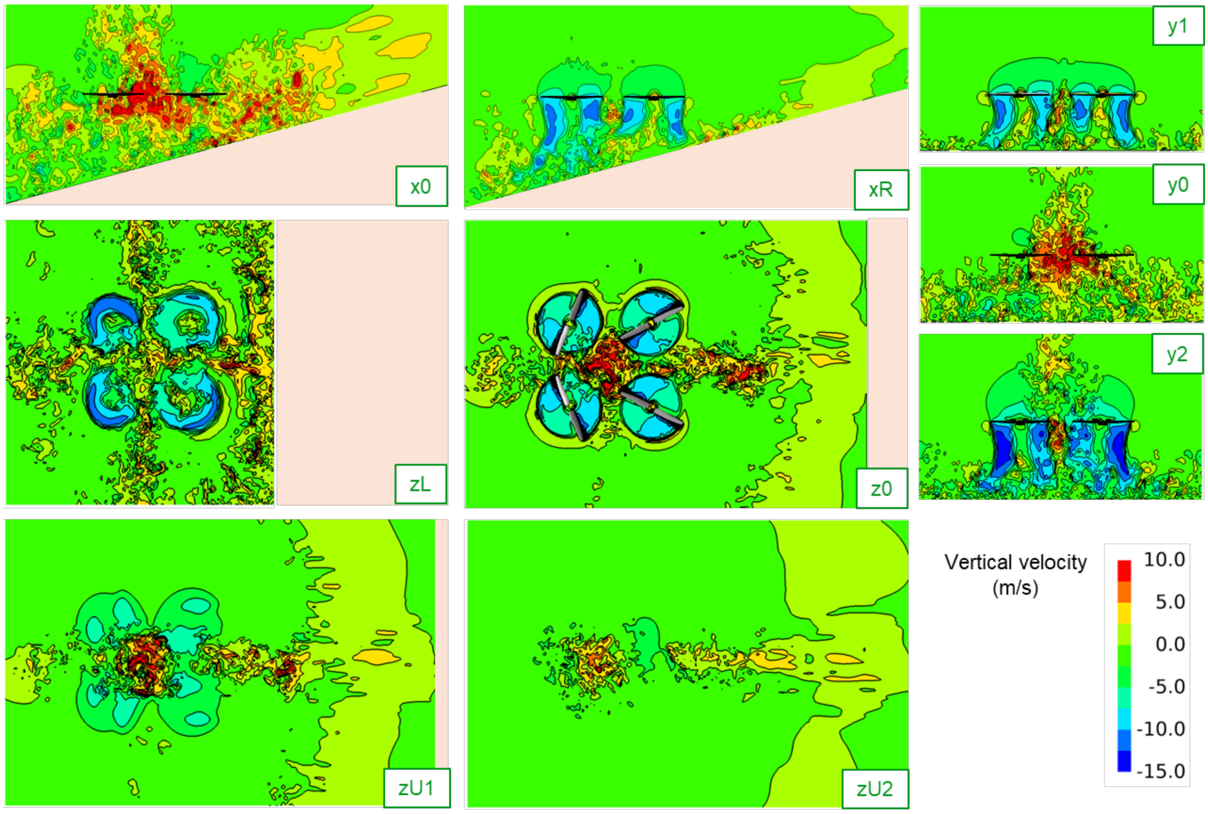


Figure 11: Flow visalization by vertical component of flow velocity field (Configuratin1, θ = 15°)

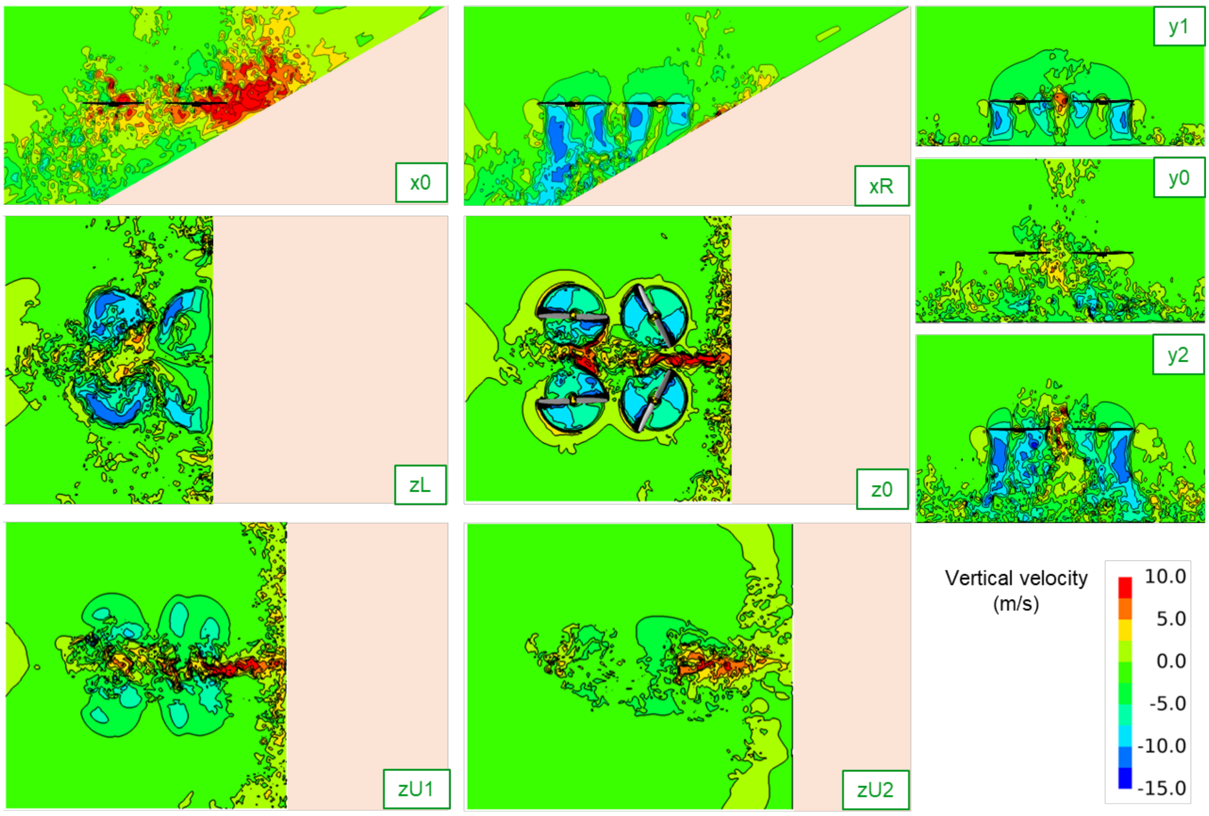


Figure 12: Flow visalization by vertical component of flow velocity field (Configuratin1, θ = 30°)

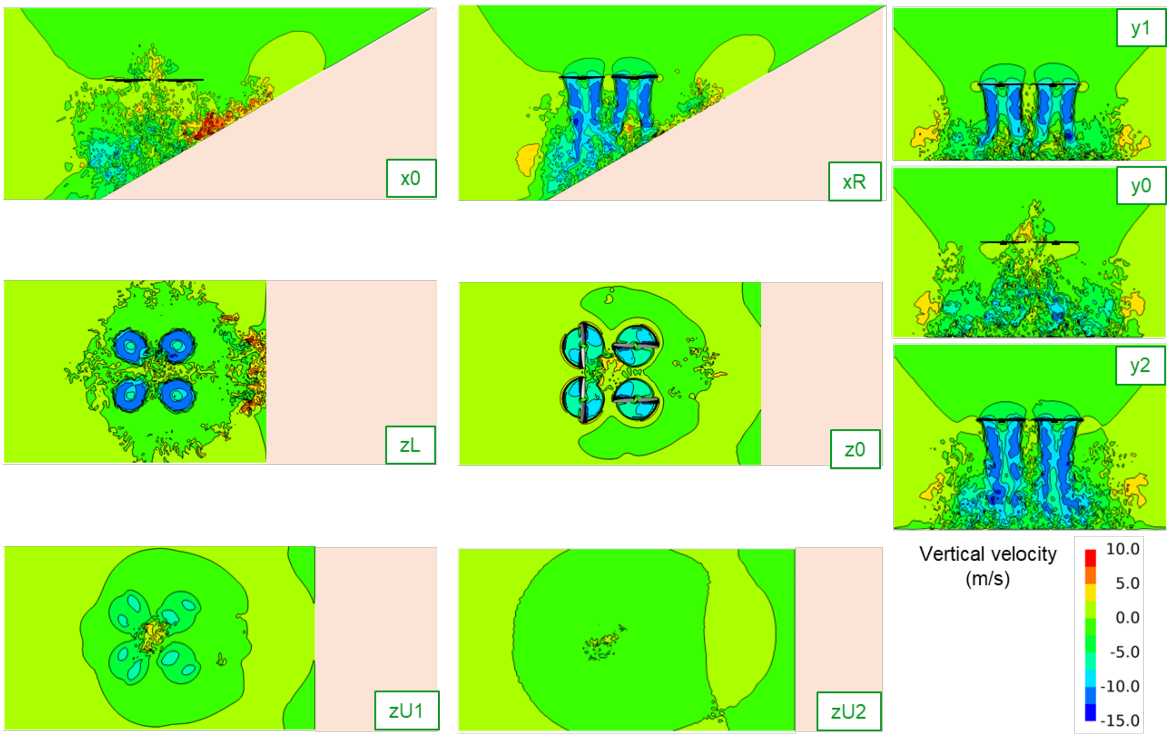


Figure 13: Flow visalization by vertical component of flow velocity field (Configuratin2, θ = 30°)

above the rotor in cross section xR in Figure 14. In the cross section zL, the upward flow region, which is in a crisscross pattern through gaps in the four rotor wake flows, is also further enhance in Figure 14 than in Figure 11. In the zL section of Figure 14, the upward flow region surrounds the two wake flows on the right due to interference with the slope. Also on the left side, the wake is disturbed due to intense upward flow. Comparing the flows in cross sections z0, y0, y1, and y2 of Figures 11 and 14, there are similar flow patterns with different intensity in the upward flow. The upward flow region is formed between the four rotor wake flows of the quadcopter and is enhanced in the direction along the inclination of the ground plane. The upward flow is more intense in Figure 14 than in Figure 11 due to the gap between the rotors and their wakes are larger. In conclusion, the difference in the deviations of the rotor power become larger since such flow characteristics exhibited more significantly.

In Figure 15, θ is 30° but the relationship of the rotor power deviation between the rotors 1,2 and 3,4 are opposite to that with θ =15° in Figure 14. Such phenomenon is not observed with other configuration. Comparing the flow patterns between Figure 15 and Figure 12, the feature of the flow field that differs the most is seen on the left side of the quadcopter in x and z cross sections. The upward flow region with high velocity appears on the left side as well as on the right side in Figure 15, while the upward flow region is mainly on the right side in Figure 13. For other cases with θ = 15°, the upward flow regions take place mainly on the right side in the figures. These tendencies can be confirmed by comparing the flow patterns in cross sections zU1 and zU2 in Figures. 11-16. The upward flow takes place in wide region on the left side in the cross section only in Figure 15. The upward flow is re-introduced to the rotors 3 and 4. Consequently, the recirculation flow takes place, and the losses increase on the rotor 3 and 4.

Figure 16 shows the flow patterns with higher altitude and θ =15°. Comparing the flow patterns with other results, the flow patterns are similar to those in Figure 11. The upward flow region is the cause of the loss on the rotors 1 and 2.

7. CONCLUSIONS

Aerodynamic and flow characteristics of quadcopters flying above a inclined ground plane have been investigated experimentally and numerically. Results are summarized as follows:

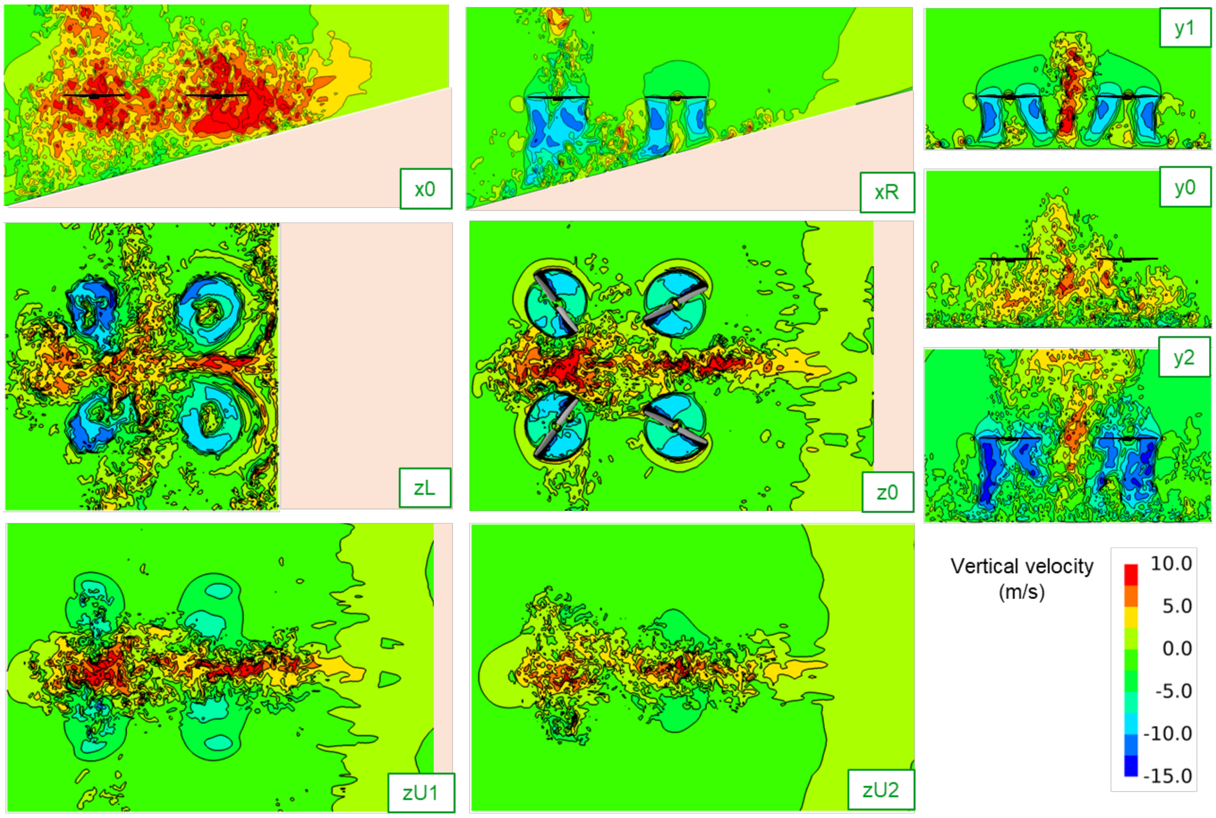


Figure 14: Flow visalization by vertical component of flow velocity field (Configuratin3, θ = 15°)

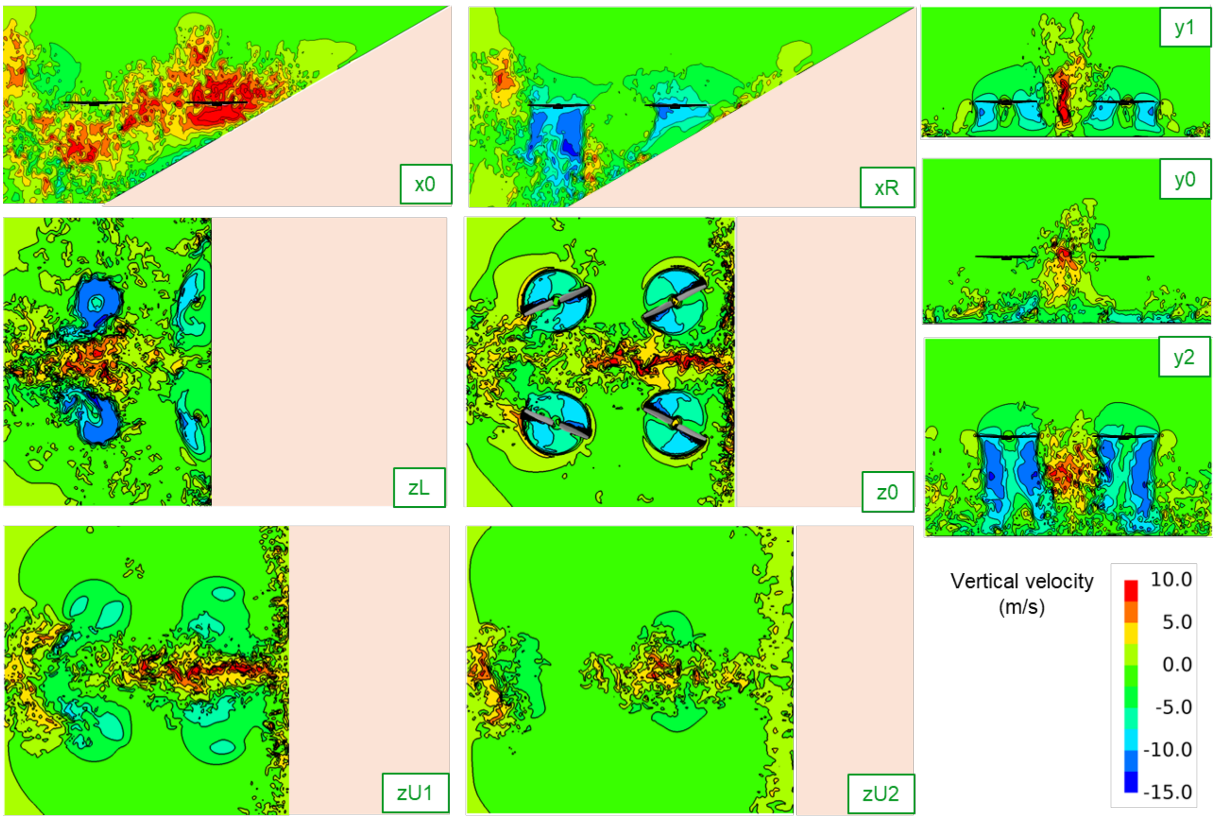


Figure 15 Flow visalization by vertical component of flow velocity field (Configuratin3, θ = 30°)

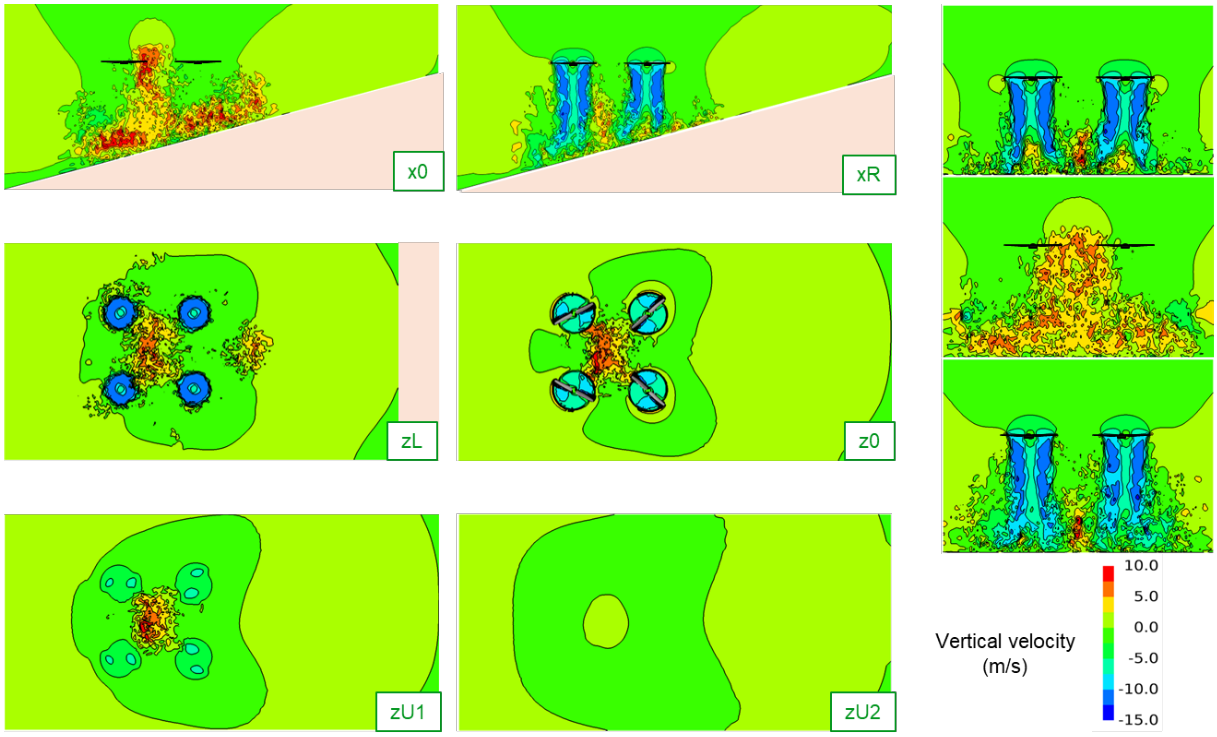


Figure 16: Flow visalization by vertical component of flow velocity field (Configuratin4, θ = 15°)

1. When the quadcopter is flying above the inclined ground wall with the thrust force are balanced, imbalance of the rotor power takes place.
2. When the two rotors are close to and other two rotor are far from the inclined ground plane, the rotor powers increase at near side and decrease at far side. For the quadcopter with large distance between the neighboring rotor tips and large inclination angle of ground plane, this relationship can be reversed.
3. The azimuthal angle is changed of 45° from the above condition, the yawing moment takes place because the rotor torque and power cannot be balanced.
4. Flow patterns are observed using numerical results. When the altitude of the quadcopter is low, upward flow takes place. The intense upward flow distributes along the ground plane inclination and between rotor wakes. The upward flow is a main cause of the loss increase due to formation of the recirculation flow. The asymmetric distribution of the upward flow is the cause of the power imbalance of the rotors.

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