Coanda effect of a propeller airflow and its aerodynamic impact on the thrust

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Received: 3 April 2020; Revised: 21 May 2020; Accepted: 24 June 2020

Abstract

The aerodynamic performance of the multi-rotor drone under the wall proximity has been investigated by experiment and numerical simulation. The propeller airflow along with the wall deflects toward the wall due to the Coanda effect, and it yields a negative impact on the aerodynamic performance. The present study aims to reveal the link between the propeller thrust and the propeller airflow under different wall proximity conditions. The deflection of the flow is confirmed by the flow visualization, and the wall pressure exhibits the signature of flow attachment both in the profiles of the mean and the fluctuation. The force measurement indicates that the degradation of the thrust is significant enough to affect the stability of the drone body. A possible reason of the decrease in thrust is found in the streamwise velocity distribution. The velocity distributions obtained by the numerical simulation indicate that the swirling motion is significantly suppressed due to the wall proximity effect. Moreover, the pressure distribution on the propeller surface explains the decrease of the thrust. The magnitude of the pressure difference becomes smaller when the propeller blade approaches very close to the wall.

Keywords: Multi-rotor drones, Propeller airflow, Coanda effect, Particle image velocimetry, Large eddy simulation

1. Introduction

Multi-rotor drones have been rapidly accepted in our society as a new transportation system, and they are now widely used for versatile applications. Safety of the drones is a primary concern to make this technology more reliable, and therefore stability of the drones is one of the most important research subjects. The drones are often used in a narrow space or close to obstacles, and the functionality can be influenced by these environmental factors. Under harsh environments, appropriate treatments are necessary to minimize the degradation of aerodynamic performance. To improve the robustness of the drones, their behavior under disturbances has extensively been studied. Typically, the relative wind velocity and proximity to the ground, the ceiling and other drones on the dynamic response are considered as in Powers et al. (2013). However, the interference with the vertical wall, which is often dismissed, is also important particularly in some applications. Recently, McKinnon and Schoellig (2020) proposed a method to evaluate the force acting on the drone body, and the force under the effect of vertical wall proximity has been estimated. As the drone body approaches to the wall, it experiences the downward force in the vertical direction and the force toward the wall in the horizontal direction. They reported the affecting distance of 0.5 m, which is comparable to the size of the drone body. Tanabe et al. (2018) performed a series of numerical simulations of the flow created by a hexarotor drone. It is stated that the proximity to the wall causes the deflection of the propeller airflow and the tilting the drone body toward the wall. They proposed a distance of at least 1.5 times of the rotor diameter for safety. Even after these studies, the relationship between the thrust and the propeller airflow has not yet been clarified when the drone body is under the wall proximity effect. Understanding the effect of the vertical wall on the force and the torque as well as the flow physics behind will definitely help to develop a better mathematical model for more efficient control strategy of the drone body.

In the fluid mechanical point of view, a jet flow close to the parallel wall deflects toward the wall due to the reaction against the blockage of entrainment. This phenomenon is known as the Coanda effect (Young, 1800), and a number of
studies have been reported in the literature (Reba, 1966). One of the simplest configuration is the plane offset jet, where a plane jet is issued parallel to the wall, and the jet exit is located with a certain distance from the wall. Nasr and Lai (1998) investigated the development of a plane offset jet in terms of the representative parameters such as the reattachment length and the profiles of the mean velocity and turbulence statistics. The plane offset jet finally turns to be the wall jet, which is one of the classical canonical flows (Launder and Rodi, 1983; Eriksson et al., 1998). In addition, the merging of dual jets, i.e., the wall jet and the offset jet, has been investigated by experiment (Nasr and Lai, 1997; Wang and Tan, 2007) and by numerical simulation (Kumar, 2015). The plane jet exhibits relatively large deflection toward the wall because of the strong entrainment. When considering the similarity with the propeller airflow, the offset ‘circular’ jet is more relevant. Shao and Law (2009) investigated circular offset jets with a slight density difference, and presented the development of the Reynolds stresses and the turbulent concentration transport. The studies on these canonical cases provide essential fundamental knowledge of the flow, but the propeller airflow is much more complex compared to the plane jet or the circular jet. Especially, the presence of the swirling motion greatly affects the development of the flow. Wei et al. (2017) studied the effect of the propeller ‘water’ flow on the plane surface. It is reported that three different regions called the free jet, impingement and wall jet regions, are observed similar to the canonical offset jet flows. They reported noticeable differences in the wall impinging motion inherent to the swirling motion.

To date, in the limit of the authors’ knowledge, there has been no report on the detailed relationship between the propeller airflow and the thrust under the effect of the wall proximity. Therefore, the present study aims to clarify the characteristics of the propeller airflow and its impact on the aerodynamic performance. The flow visualization, the wall pressure measurement, the force measurement and the two component two dimensional particle image velocimetry (2C2D-PIV) are applied. Moreover, to complement the experimental observations, the flow is reproduced by large eddy simulations (LES) with three different propeller–wall distances. The LES provides the quantity that is difficult to be obtained by experiment, for example, the instantaneous pressure distributions on the propeller surface.

2. Setup of the experiment
2.1. Propeller model and the coordinate system

A propeller with three blades as shown in Fig. 1 is used for the present study. The diameter of the propeller $D = 130$ mm, and the diameter of the hub is $25$ mm. The chord length and the blade angle vary against the radial position, $r$. The maximum chord length is $18$ mm, and it is $9.3$ mm at the propeller tip. The blade angles at the root and at the tip are $18^\circ$ and $5.4^\circ$, respectively. The propeller pitch varies with the radial position.

A propeller was driven by a brushless outrunner motor for Parrot Bebop 2. The current was supplied to the motor through the electric speed controller (ESC BLHeli-12A, SKYRC) connected to the DC power supply (PMC35-3, Kikusui). The rotation speed of the motor was controlled by the pulse width modulation control using Arduino (Arduino Uno R3). The rotation speed of the motor was fixed to 7500 rpm where the drone was assumed to be in the hovering condition.

The Cartesian coordinate system is employed in the present paper, and it is defined at the center of the propeller. The axial direction is $x$, the wall normal direction is $y$, the spanwise direction is $z$. The distance between the propeller tip and the wall is defined as $h$. 

![Fig. 1](image_url)
2.2. Flow visualization

The flow visualization experiments of the propeller airflow were prepared. The smoke for flow visualization was generated by a smoke generator (Model 8304, Kanomax). A laser beam from a continuous wave laser with the output power of 5 W (MGL-N-532, CNI) was shaped to a planar sheet aligned in $x-y$ plane passing through the propeller axis. The field of view was adjusted to approximately $6.4D$ in $x$ and $3.3D$ in $y$ directions. The thickness of the light sheet was tuned to approximately 2 mm using the combination of plano convex–concave lenses. The motion of the smoke was recorded by a digital camera (DSC-RX100M5, Sony) at 960 fps.

2.3. Pressure measurement

The pressure distributions on the wall caused by the propeller airflow were captured at pressure taps. The diameter of a pressure tap is 2.0 mm. The gauge pressure was measured using a low differential pressure transducer (DP45-14, Valdyine; PA701, Krone) at nine points distributed non-equidistantly. The pressure tap and the transducer were connected with a silicon rubber tube with the length of 570 mm. To check the unsteady response of the pressure measurement system, the analytical formula by Bergh and Tijdeman (1965) is employed. Although the frequency response curve exhibits a resonance peak around 100 Hz, it should not make a significant impact on the measured level of the pressure fluctuation since the pressure fluctuations are mainly contributed from the frequency range below 100 Hz. The output voltage was acquired using a data logger (NR-500 and NR-HA08, Keyence) at the sampling frequency of 20 kHz for 60 s at each pressure tap.

2.4. Force measurement

The force was evaluated by an electric scale (TE412-L, Sartorius) having the resolution of 0.0981 mN. A propeller base was fixed on the slide stage (SGSP33-200, Sigma Koki) with the positioning repeatability of ±4 μm. The propeller position was settled upside down so that the propeller thrust could be measured using the electric scale as an additional weight. The axial thrust was measured at 14 different propeller-wall distances. The data of the electric scale were captured at 5 Hz, and 100 samples were averaged to obtain the mean force.

2.5. Velocity measurement by large field PIV

The velocity fields of a propeller airflow were measured by the 2C2D-PIV. The setup of PIV is shown in Fig. 2. The propeller was placed on the support with the height of approximately 350 mm. To avoid the ground effect, the propeller airflow was directed upward. The distance between the propeller and the ceiling of the room is approximately 3.5 m.

A laser beam from a pulsed laser with the maximum output energy of 140 mJ/pulse (Evergreen, Quantel) was guided and shaped to a planar sheet parallel to $x-y$ plane passing through the center of the propeller. The thickness of the light sheet was adjusted to approximately 2 mm using a plano convex–concave lens system. The tracer particles (Bis(2-ethylhexyl) Sebacate) with the diameter of 0.3–1.0 μm generated by a particle generator (PIVpart14, PIVTEC) were introduced from the upstream of the propeller. Images of particles were recorded using three cameras: two CMOS cameras (CLF-C2880M, Imperx, 2832 × 2128 px) with 50 mm F#1.4 lenses (Samyang 50 mm F1.4 AS UMC) and a CCD camera(ICL-B2020M, Imperx, 2048 × 2048 px) with a 35 mm F#1.4 lense (Samyang 35 mm F1.4 AS UMC). The cameras and the laser were synchronized by a delay pulse generator (Quantum composer 9618). The image acquisition was performed at 2 Hz.

Fig. 2 Schematic of the PIV experiment.
Fig. 3  Photos of the propeller airflow visualization, (a) $h = 0.5$ mm, (b) $h = 45$ mm, (c) $h = 90$ mm and (d) no wall. The laser sheet is aligned in $x - y$ plane passing through the propeller axis. Four consecutive frames with the time separation of 31.25 ms are presented from left to right. The length corresponding to the propeller diameter is indicated by a white line in the left most photo.

To capture a wide region of the flow in the streamwise direction, three cameras were arranged in line as shown in Fig. 2. The fields of the two adjacent cameras are slightly overlapped so that the camera calibration can reconstruct a large consolidated field of view. The calibration grid was recorded for the conversion of the image and physical coordinate. The 2nd order polynomial function is used for mapping between the image coordinate and the physical coordinate (Solooff et al., 1997). To obtain better overlap, the mapping function of each camera was shifted based on the results of the cross correlating the particle images of the overlapped region from different cameras recorded at the same instant. This procedure is similar to the self-calibration method for the stereo PIV (Wieneke, 2005) and the position matching of two cameras in sub-pixel level can be achieved. The size of the consolidated dewarped image is $680 \times 235$ mm in the physical coordinate and $5781 \times 1998$ px in the image coordinate for $h = 90$ mm case. The raw particle images have a resolution of $119–143 \mu m/px$, and $118 \mu m/px$ for the dewarped images.

A set of consolidated particle images was processed by an in-house 2C2D-PIV code implemented in reference to books (Adrian and Westerweel, 2010; Raffel et al., 2018). It employs an FFT based multi-pass cross correlation method with three point Gaussian subpixel interpolation and the outlier detection by Westerweel and Scarano (2005). Details of the PIV analysis are found in our previous paper (Naka et al., 2020). For the present analyses, the interrogation window with the size of $128 \times 128$ px was used for the first pass, and $64 \times 64$ px for the second, $32 \times 32$ px for the final pass. The interrogation window size of 32 px gives the spatial resolution of approximately 3.76 mm. The spacing between adjacent vectors was set to 16 px, which gives 50 % window overlap. The statistics were evaluated by averaging 220 velocity snapshots.

3. Experimental results

3.1. Flow visualization

The results of the flow visualization are shown in Fig. 3. The effect of the wall proximity is clearly observed for all
three cases (a)–(c), $h = 0.5, 45, 90$ mm, comparing with ‘no wall’ case. The mean flow is deflected toward the wall. For the case (a), the smoke is attached to the wall near $x/D \sim 2.4$. As the propeller moves further away from the wall, the attachment point is found to be in more downstream. For the case (b), it is attached near $x/D \sim 3.2$, and near $x/D \sim 4.0$ for the case (c).

### 3.2. Wall pressure measurement

Figure 4 indicates the distributions of the mean values of the wall pressure and the rms values of the wall pressure fluctuation. The wall proximity effects are clearly visible in both mean and rms values. For the mean pressure distributions, it varies significantly for the case with $h = 0.5$ mm. It is positive for close to the propeller and then decreases down to negative between $1.6 \leq x/D \leq 3.5$, where the flow attachment is observed in Fig. 3. This behavior is visible for $h = 45$ mm with less magnitude, and for $h = 90$ mm, the variation of the mean pressure is barely noticeable. It is noted that the present results are in accordance with the one in the offset jet and the dual jet cases (Kumar, 2015). The mean wall pressure is negative in the upstream of the reattachment point and positive in the downstream.

For the pressure fluctuation, the peak of the pressure fluctuation is observed near $x/D \sim 2.7, 4.0$ and $5.0$ for $h = 0.5, 45$ and $90$ mm. These positions are close to the region where the flow is attached in the flow visualization in Fig. 3 as well. This leads the explanation that the pressure fluctuations are caused by unsteady flapping motion of the propeller airflow.

### 3.3. Force measurement

#### 3.3.1. Effect of the wall proximity on the propeller thrust

The effect of the wall proximity on the propeller thrust is presented in Fig. 5. It indicates the change in the thrust with respect to the value with no wall. For $h/D \leq 0.3$, there
is a clear tendency in declining thrust as the distance becomes smaller. At the closest position, $h = 0.5$ mm, the thrust decrease in $35$ mN is observed. For the larger distance, the thrust seems to decrease again in $0.5 \leq h/D \leq 0.77$. For the moment, no plausible reason is found to explain this behavior. They are possibly inherent to the present experimental setup and environment. Nevertheless, at least it is confirmed that the tendency presented in Fig. 5 is not an artifact but repeated in several experiments. It is noted that the thrust without wall proximity effect is $0.64$ N, and the largest thrust decrease corresponds to $5.2\%$ of the thrust.

3.3.2. Impact of force declination on stability

The effect of the wall proximity in the thrust can be up to $\Delta F = 35$ mN, where $\Delta F$ denotes the difference in the thrust compared to the value without the wall proximity effect. Considering the stability of the quadrotor, when one of four propellers suffers such degradation, the force balance of the propellers becomes out of equilibrium, and the drone body would be tilted unless no feedback control for correction is applied. Here, the impact against the rotational stability of the quadrotor is analyzed. The rotation of the drone body is described by the equation of the rotational motion.

$$I_b \ddot{\theta}_b = \Delta F L,$$

where $I_b$ is the moment of inertia of the drone body, $\theta_b$ is its angle position, and $L$ is the distance between the diagonal propellers. Also, $\dot{}$ (dot) and $\ddot{}$ (double dot) denote the first and the second order derivatives in time $t$, respectively. By considering initial conditions, $\theta_b = 0$ and $\dot{\theta}_b = 0$ at $t = 0$, integrating equation (1) in time gives

$$\theta_b = \frac{\Delta F L}{2I_b} t^2,$$
When $I_b$ can be estimated with the assumption that the shape of drone body is approximated by a disk,

$$I_b = M \left( \frac{9}{16} L^2 + \frac{1}{12} H^2 \right),$$

where $M$ and $H$ are the mass and the height of the drone body, respectively. It is noted that the axis of the rotation is the edge of the drone body. Assuming a typical drone body with $M = 0.5$ kg, $L = 240$ mm and $H = 50$ mm, and taking 5.2% decrease in thrust, the tilting angle would be 28.4° in 0.5 s, which is not negligible for the stability of the quadrotor.

### 3.4. Velocity field

Figure 6 shows the distributions of the mean streamwise velocity in $x-y$ plane at different propeller–wall distances. For all the cases, the distribution indicates two separated high velocity regions in upper and lower part of the propeller. In Fig. 6(a), the velocity contour line starts to deflect from $x/D \approx 1$, and the mean flow is attached to the wall in downstream. In Fig. 6(b), the deflection is less pronounced but it is still visible in the downstream region, $x/D \geq 2.5$. In Fig. 6(c), the deflection is not clearly observed in the contour line and the flow seems to be symmetric around the axis up to $x/D \approx 3$ even though slight asymmetry is found in further downstream, $x/D \geq 4$.

The velocity profiles at representative streamwise positions are presented in Fig. 7. Comparing profiles at the most upstream location $x/D = 0.15$, the asymmetry in the profile for the case with the smallest propeller–wall distance is...
significant. On the peak in the wall side, 34 % reduction of the streamwise velocity is observed. In terms of the momentum balance, the decrease in the streamwise velocity can directly be related to decrease in the thrust. For $h = 45$ mm, the velocity decrease still exists but is less distinctive, and for $h = 90$ mm, the profiles are symmetric and no wall effect is found apparently at the most upstream location. As it moves downstream, the two peaks disappear and a single peak locates close to the wall like a wall jet. For $h = 0.5$ mm, this process happens very quickly. It is noted that even for further propeller positions, the velocity profiles near the wall exhibit the boundary layer like shape in the downstream region.

Figure 8 indicates the distributions of the wall normal velocity field and the velocity vectors around the propeller. For $h = 90$ mm, in the region just downstream the propeller, the wall normal velocity distribution indicates the flow converging toward the axis, upward in the bottom part and downward in the top part. This can be explained due to the pressure distribution in this region. Near the propeller axis, the pressure is significantly lower than the atmospheric due to the swirling motion induced by the propeller. The distribution is quite similar for $h = 45$ mm, and in fact, the effect on the wall normal velocity components is not significantly appeared even in the further downstream region. This infers that the difference in the streamwise velocity distribution is not directly contributed from the wall normal transport of the fluid in this plane, and it is possibly due to the spanwise motion induced by the swirling motion. On the other hand, the distribution is asymmetric for $h = 0.5$ mm. Especially, in the bottom part, the upward motion is suppressed due to the blockage of the wall. This emphasizes the downward motion in the center part.

4. Setup of the numerical simulation

4.1. A numerical propeller model

A 3D propeller model has been prepared for the numerical simulations. To reproduce the shape of the propeller used in the experiments as precise as possible, three parameters of the propeller, i.e., the wing chord length, the blade angle and the thickness, were measured at different radial positions. The measured values are interpolated by functions as presented in Fig. 9. The wing chord length is interpolated by 3rd order polynomial function, the thickness is represented by a linear...
function. The blade angle $\alpha$ is expressed as follows:

$$\alpha = C_1 \arctan \left( \frac{C_2}{2\pi r^*} \right),$$

where $r^*$ is the normalized radial position $r^* = r/R$; $R$ denotes the radius of the propeller. The two constants, $C_1$ and $C_2$ are determined by the measured blade angle at the wing tip and the wing root. The NACA44 series is chosen for the shape of the wing section. A point cloud representation of the wing surface is generated based on these functions, and a 3D solid model is constructed. The numerical propeller model might not be exactly the same with the one used in the experiment because of the limited measurement data or available information of the propeller geometry. Nevertheless, at least the inspection by eye gives a good coincidence, and therefore it is enough to provide complementary information regarding the propeller airflow near the wall.

### 4.2. Meshing and simulation parameters

The present computation has been performed using an open source package for computational fluid dynamics, OpenFOAM. The propeller model is placed in a computational domain as presented in Fig. 10. It is a rectangular box of $1800 \times 600 \times 600$ mm in $x$, $y$ and $z$ directions, and decomposed in $192 \times 96 \times 96$ cells using blockMesh utility. The cell points are placed non-uniformly in all three directions. The mesh is denser in the region closer to the wall and the propeller. A short cylinder surrounding the propeller is prepared to deal with a dynamic mesh functionality called arbitrary mesh interface. The meshing of the propeller shape is done with SnappyHexMesh utility. The refinement level controls the ratio of the background mesh and the mesh around the propeller. Three different configurations of the propeller–wall
distance, i.e., \( h = 2 \text{ mm}, 35 \text{ mm} \) and \( 95 \text{ mm} \), have been prepared. The meshing condition is summarized in Table 1. For cases 1, 2 and 3a, the computational grid composes of approximately 2 million elements. The dependency of the meshing conditions is checked with two other cases with more grid points and a higher refinement level, named as cases 3b and 3c. The generated 3D models of the propeller for cases 3a–3c are shown in Fig. 11. The comparison indicates that there is no major difference in the velocity distributions among three different meshing conditions. Therefore, the results with 2 million cells, i.e., cases 1–3, are shown in the later sections.

The numerical simulation of the propeller airflow has been performed using OpenFOAM versions v1612 and v1906. The large eddy simulation (LES) has been performed with a solver called pimpleFoam for incompressible transient flows with dynamic mesh functionality. The rotation speed of the propeller was set to 7200 rpm. The governing equations are the filtered continuity and the Navier-Stokes equations with the Smagorinsky subgrid scale model. The Smagorinsky coefficient \( c_s \) is defined using \( c_k \) and \( c_e \) as \( c_s = (c_k/c_e)^{1/4} \), where \( c_k = 0.05 \) and \( c_e = 1.0 \) resulting in \( c_s = 0.106 \) which is close to the value commonly used for the wall bounded turbulent flows (Pope, 2001). The other details of the settings of numerical simulation are described in appendix A.

A series of computations has been performed on a computing node (PRIMERGY RX2530 M4, Fujitsu) at Ikuta media support office, Meiji university. Each node has two Intel Xeon Gold 6142 processors and 96 GB RAM. Each run of the simulation has been performed with 32 cores on a single node. The time step is adjusted during the computation so that the Courant number does not exceed 1.0, and the average value of the time step is approximately 4.2\( \mu \text{s} \). Average computational time in the wall clock time for one step is 1.44 s. For the statistical evaluation, 225 samples are corrected between \( t = 0.5 \text{ s} \) and \( t = 5 \text{ s} \) with the separation of 0.02 s.
4.3. Results of the large eddy simulation

Figure 12 shows the distributions of the streamwise mean velocity for the different propeller–wall distances. The distributions are strikingly similar to the ones from the experiments shown in Fig. 6. This validates that the results of the present LES can be used for the complementary analyses. The important feature in Fig. 12(a) is that the shape of the contour line of the upper part is significantly deflected near \( x/D = 2 \). This is also confirmed in the experiment in Fig. 6. Moreover, the results obtained in the propeller water flow affected by the wall (Wei et al., 2017) exhibit very similar tendency. This infers that such a development is commonly observed in various conditions. The effect of the wall is observable in \( x/D \geq 4 \) for \( h = 35 \) mm and in \( x/D \geq 5 \) for \( h = 95 \) mm.

Figure 13 presents the velocity distributions in \( y-z \) plane at different \( x \) locations. For \( h = 2 \) mm, the velocity distribution is already skewed in the most upstream position. Swirling motion away from the wall is weaker than that toward the wall. The spanwise flow near the wall mostly goes along with the wall and the ejection motion is significantly suppressed. This asymmetry triggers the breakdown of the main longitudinal vortex, and the main part of the flow is shifted towards the wall due to the attenuation of the upward motion. For \( x/D \geq 4.62 \), the spanwise diverging flow is observed near the wall, and the location of the stagnation is observed slightly off the center. Then, the flow gradually slows down due to the friction with the wall.

For the cases with further propeller–wall distances, \( h = 35 \) and 95 mm, the velocity distributions exhibit the clear single vortex pattern at \( x/D = 1.54 \). For \( h = 35 \) mm, the vortex starts to interact with the wall from \( x/D = 4.62 \). Similar to \( h = 2 \) mm, the sweeping motion is pronounced, and spanwise diverging flow is induced near the wall. For the furthest position, \( h = 95 \) mm, though the effect of the wall is less pronounced compared to the two other cases, the distribution is apparently asymmetric about the wall normal direction. In all the cases, the development of the flow...
seems to be significantly affected by the swirling motion. The interaction of the swirl and the wall results in the complex development, which is very different from the simpler configurations such as a plane jet or a circular offset jet.

In terms of the thrust of the propeller, it is directly linked to the pressure on the propeller surface. Figure 14 presents the distributions of the pressure on the propeller surface for $h = 2$ mm. The pressure on the blade closest to the wall exhibits smaller pressure magnitude both on positive and negative sides, which results in decreasing the thrust. This can be explained by the momentum loss due to the friction in the propeller airflow close to the wall. Furthermore, the blade suffers the force fluctuation at the rotation frequency, and this would lead to a potential risk of the fatigue fracture. It is noted that the near wall effects in the other propeller–wall distances (not shown) are much less significant.

In the present study, the airflow generated from a single propeller has been investigated. However, it is reported...
that the near wall effect can be different between the single propeller flow and the flow generated by the multi-rotor configuration (Tanabe et al., 2018). The behavior of the flow from the actual multi-rotor drone will be investigated in our future study.

5. Conclusion

The propeller airflow under the effect of the wall proximity has been investigated by experiment and numerical simulation. The experiments have been performed in a single propeller configuration. From the smoke flow visualization, the deflection of the flow is clearly observed. The mean wall pressure and the wall pressure fluctuation exhibit signatures of the Coanda effect. The decrease in the thrust due to the wall proximity is observed, and the impact is significant in terms of the stability of the drone body. The velocity fields obtained by 2C2D-PIV provide the quantitative information of the flow. The wall proximity effect is observed in the development of the streamwise velocity distribution. The LES was set up so that the propeller airflow interfered by the wall is reproduced. The 3D numerical model of the propeller is represented by the radial distributions of the three parameters, the chord length, the blade angle and the thickness. The results of the numerical simulation are compared with those from experiments. The streamwise mean velocity distributions agree well confirming the validity of the present numerical simulation. The swirling motion of the propeller airflow is greatly interacted with the wall when the propeller is placed close to the wall. The key mechanism is the suppression of the ejecting motion, which shifts the higher velocity region towards the wall. The cause of the decrease in the thrust is found in the pressure distributions on the propeller surface. This pressure decrease can be related to the momentum loss observed in the mean streamwise velocity distribution. The present study will provide fundamental understanding of the interaction between the propeller airflow and the wall, and then it will be useful for further investigation of the wall proximity effect of the multi-rotor drones.

Acknowledgement

The authors acknowledge Ikuta Media Support Office at Meiji university for providing computer resources of their “PC Cluster system”.

Appendix A: Details of numerical simulation using OpenFOAM

The details of numerical simulation are described in this appendix. The boundary conditions are described in Table 2. For the initial condition, all the variables have zero values at all cells in the domain. Choices of the numerical schemes
Table 2 Boundary conditions.

| variable      | target face | condition                      |
|---------------|-------------|---------------------------------|
| velocity      | wall        | no slip                         |
|               | inlet       | fixed value at 0.1 m/s          |
|               | outlet      | inletOutlet with zero inlet velocity |
| pressure      | wall, inlet | zeroGradient                    |
|               | outlet      | fixed value at 0 Pa             |
| eddy viscosity| wall        | nutkWallFunction                |
|               | inlet, outlet | calculated                      |

Table 3 Numerical schemes.

| target scheme | target   | scheme                      |
|----------------|----------|-----------------------------|
| ddtSchemes    |          | Euler                       |
| gradSchemes   | grad(p)  | Gauss linear                |
|               | grad(U)  | cellLimited Gauss linear 1  |
| divSchemes    | div(phi,U) | Gauss linearUpwind grad(U)                                           |
|               | div((nuEff*dev2(T(grad(U))))) | Gauss linear                 |
| laplacianSchemes |        | Gauss linear limited corrected 0.33 |
| interpolationSchemes |    | linear                      |
| snGradSchemes |          | limited corrected 0.33      |

Table 4 Solver setting.

| target | solver     | smoother                  |
|--------|------------|---------------------------|
| pressure | GAMG     | DICGaussSeidel            |
| velocity | smoothSolver | symGaussSeidel            |

Table 5 Parameters for PIMPLE loop.

| parameter       | value |
|-----------------|-------|
| correctPhi      | no    |
| nOuterCorrectors| 1     |
| nCorrectors     | 2     |
| nNonOrthogonalCorrectors | 0     |

and the solver parameters are summarized in Tables 3 to 5. Readers may refer to the document of OpenFOAM for the descriptions of solvers (OpenCFD Limited, 2019).

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