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Wind Effect on Aerodynamic Optimization for Non-planar Rotor Pairs using Full-scale Measurements

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Abstract Aerodynamic force measurements and a flow field survey were performed on two original non-planar rotor pairs in order to investigate the effect of wind disturbances on aerodynamic performance at low Reynolds numbers and provide effective data for the design of a rotor system for a small unmanned aerial vehicles with different disk plane angles φ and rotor spacing ratios S/D. Experiments were performed on a test-platform based on the use of two proposed rotor pairs which permit characterization of the aerodynamic performance as a function of wind turbulence with a frequency in the range from approximately 0 to 4 m/s. The measurement results show that variations in wind speed cause large variation in the mean values of the lift force and power consumption. The combined optimal configuration is S/D =1.0 with $\varphi = 50$ deg for the non-planar rotor systems with good wind resistance.

Keywords Low *Re* · Wind tunnel · Aerodynamic force · Optimal configuration

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Nomenclature

D	Rotor diameter (mm)
d	Shaft diameter (mm)
F	Lift force (g)
Ω	Rotational speed (rpm)
C_p	Power coefficient
P	Power (W)
Q	Torque (Nm)
l	Rotor spacing (mm)
φ	Disk plane angle
C_{T}	Thrust coefficient
b	Average blade chord (mm)
Re	Reynolds number
h	Rotor height (mm)
z	Normalized rotor height
M_{tip}	Mach number
S/D	Rotor spacing ratio
v	Wind speed (m/s)

1 Introduction

In the past few decades, small unmanned aerial vehicles (SUAVs) with multi rotors have received much attention due to their special aerodynamic performance at low Reynolds numbers (*Re*) [1–3]. At these values of Reynolds number, viscous effects in the flow are more dominant, where boundary layers are thick and undergo several complex phenomena. Separation, transition, and reattachment can all occur within a short chordwise distance, forming laminar separation bubbles that have a strong adverse effect on the lifting surface characteristics including reduced maximum lift coefficients and increased drag coefficients. It is commonly known that this basic flow phenomenon is responsible for the involved viscosity [4]. Less known is that within a certain range of *Re*, external disturbances such as wind gust can cause variations in lift force or extra power consumption for the rotor system at hover mode. To achieve a better performance under the influence of the wind gust, a better wind resistance can be obtained by reducing the large hover power requirements while simultaneously stabilizing the lift force in the same time. This phenomenon was experimentally discovered by Conlisk [5]. The first experiments were undertaken by Hoffmann et al., however, there are only a few studies available on these effects [6, 7]. Additionally, hovering is an intrinsically high-powered flight state with considerably larger energy requirements than cruising. A strategy for improving the hover efficiency to obtain lower power requirements and a larger lift force through optimal configuration of the rotor system while taking the wind effect into consideration is a key vehicle characteristic that must be carefully addressed. To the best of the authors' knowledge, the effect of wind turbulence at such low values of *Re* has been rarely considered for most planar rotor systems ($\varphi = 0$ deg). This is because the rotor performance with a wind gust is very different than at constant free stream velocity in hover mode. When faced with a wind gust, there is an effective change in velocity may increase in thrust and a reduction simultaneous reduction in power which would lead to an increase in payload, a more compact design, and an increase in endurance. A study by Iungo [8] has been cited in almost all studies of the wind effect on the flow around a rotating system, and this study investigated the flow where a low *Re* was expected. In contrast with the large number of studies on planar rotor pair [9–11], there are not many studies focused on the wind effects with low *Re*. Since the flow in this case has a smaller momentum acting on the rotor system [11], only a Large Eddy Simulation (LES) of the flow over a rotating rotor was performed with the wind turbulence at $Re = 10^4$ [12]. Consequently, the results for low *Re* force coefficients are still not available. Additionally, the detailed process of how the wind disturbance affects the aerodynamic performance, especially at low *Re*, has neither been fully investigated nor fully understood.

In this paper, we propose two non-planar rotor pairs with arbitrary thrust and torque. The SUAV's aerodynamic analysis is complicated by the requirement to minimize the overall size of the vehicle (sometimes defined as the vehicle's maximum dimensions). This restriction is also required to maximize the available aerodynamic efficiency, which means maximizing the lift force or minimizing the power consumption. Although much work has been performed on planar rotors, there is little data existing on the performance of non-planar rotors in the low *Re* region. In response to this dearth of reliable information, in this paper, a systematic, experimental investigation is conducted to obtain the hover characteristics for this configuration. The investigation has a two-fold goal: first, to investigate the improvements in performance that can be achieved from using a non-planar rotor configuration by considering the wind effect, and second, to acquire a body of experimental data that can be used for the validation of analytical, predictive tools, and as guidelines for the design of more efficient and capable MAVs.

To design an optimal configuration for non-planar rotor pairs with good wind resistance, we developed an experimental methodology to optimize the arrangement of the rotor pair to achieve the best aerodynamic performance in hover flight. It is known that rotor interference affects the aerodynamics of the rotor pair, but it is unclear how much of an effect the wind gust has on the performance. Therefore, it is not trivial to study the flow performance around a rotating rotor pair in a wind tunnel, since the drive mechanism may appreciably influence the disturbances on the flow field of the rotor pair appreciably. Finally, a different wind speed value is used to determine the aerodynamic performance of rotating rotor pair for a broad range of *Re*, and the flow fields are experimentally investigated using visualization methods such as the aerodynamic force and power consumption measurement. In this aerodynamic analysis, the face-to-face rotor pair and the back-to-back rotor pair that can achieve global analysis are defined for the first time in order to extend our results by taking into account aerodynamics interference in low *Re* environments into account. And a different wind speed, *Re*, the rotor spacing and disk plane angle are also considered as key test parameters to perform a series of experiments to show how the power and lift change as a function of time as the rotor enters a wind gust.

2 Experiments

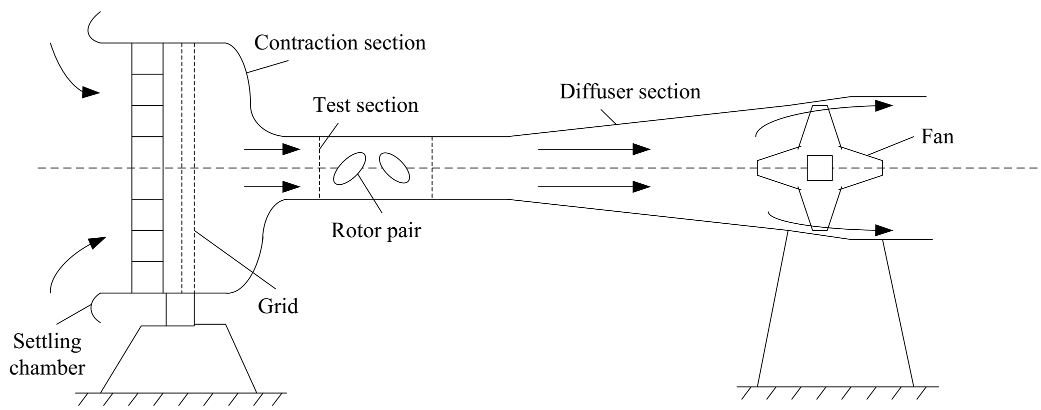
2.1 Experimental Setup

As shown in Fig. 1a, the experiments were conducted in a low speed wind tunnel with an open return and jet testing section [13, 14]. The nozzle opening had a rectangular exit area of 1.5 m ×1.5 m and the test section length is 2 m. Since the wind speed is usually less than 5 m/s in the working environment, three different typical velocities (v = 0, 2.5 and 4 m/s) were considered. The local velocity differences in the approach flow at the nozzle exit area were less than 1.3 %.

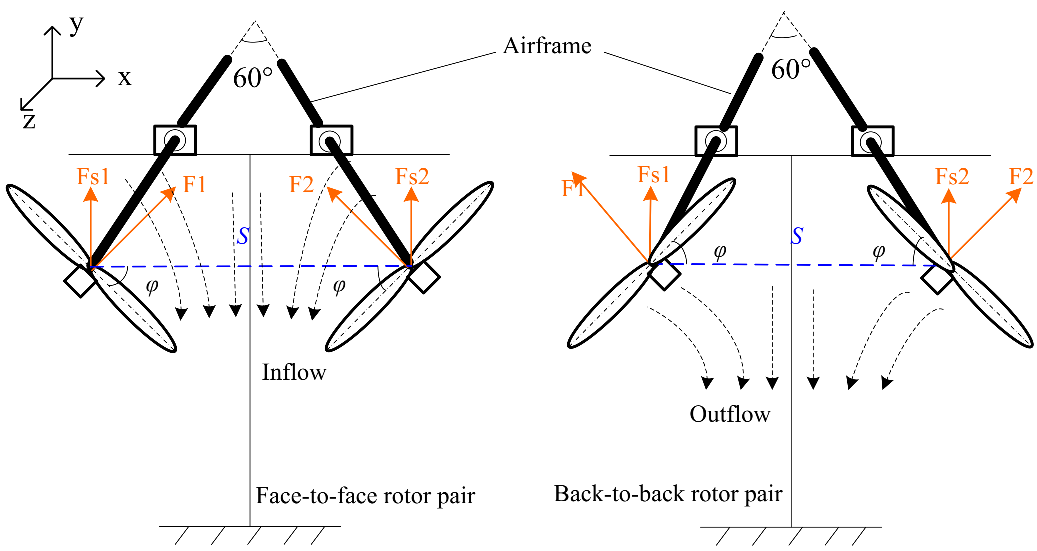
According to Ref [15], the height of the vehicle above the ground affects the intensity of the up-wash that is produced underneath the vehicle. The normalized rotor height above the ground as a geometric parameter depends only on the scale of the model which is defined as follows:

$$z = h/D \tag{1}$$

The maximum rotor height causing an in-ground effect or a wall effect is less than 3.5 times of D. Since the rotor diameter D is 400mm, the rotors were fixed at a height of 1.5 m which is high enough to avoid



(a) Sketch of a side view of the wind tunnel



(b) Installation of the rotor pairs

Fig. 1 Experimental setup

any wall effects on the measurements. The overall set-up was consisted of two rotors, which were driven by internal DC-motors. Therefore, the rotor pair could be spun across the range from 1500 to 2300 RPM, which corresponds to *Re* from 0.74 $\times10^5$ to 1.13 $\times10^5$ for a diameter of $D = 400$ mm. Both sides of the shafts ($d = 10$ mm) were fixed with a clamp. Due to size restriction and inability to have a rotor spacing less than 400 mm, the total length was assumed to range from 400 mm ($S/D = 1.0$) to 720mm ($S/D = 1.8$). It is also considered that rotors also can be orientated with different disk plane angles. The disk plane angle φ was varied from 0 to 50 deg for every 10 deg, and the counterclockwise direction was assumed to be the positive direction. The test parameters are shown in Table 1.

The lift force F was measured independently in the y-direction with a thrust sensor (CZL605, China) that was placed directly under the rotor shaft. The power consumption P was obtained with the recorded current and voltage. Further details on the structure can be seen in Fig. 1b. Using this configuration, the effect of the wind on the rotor system could be accurately simulated. All of the force measurements were sampled and averaged over 10 s, and three to six test runs were performed to assess its repeatability.

2.2 Uncertainties

An uncertainty analysis of all the key parameters was performed to determine accuracy of the test measurements. Since no flow visualization was performed for this type of non-planar rotor pair, the overall uncertainties of the force coefficient and the power coefficient are estimated according to the methodology of Coleman and Steele [16]. Since the fixed pitched rotors were used, the main sources of error in the experiments were the standard deviations of the rotational speed and the mean voltages from the thrust and torque sensors. The rotational speed error is related to a finite number of magnets that excite the sensor. In the current tests, 24 magnets were used which means an uncertainty of a 1/24 revolution per sample for any measured rotational speed. By counting the number of times a magnet passes over a sensor in one second, the error is found to be 1/24 ×60 = 2.5 RPM. If a sampling time of four seconds is considered, the uncertainty in the rotational speed is 0.625 RPM.

The Kline-McClintock (Ref. [17]) method for error propagation was used to calculate the uncertainty of the measurements. The uncertainty in the force and the power coefficients was calculated by considering the errors in the measurements of the thrust torque and the rotational speed. Starting with the previously defined force and power coefficients, the following equations were obtained.

For the force coefficient:

$$C_F = \frac{F}{\rho A \Omega^2 R^2} \tag{2}$$

Applying the Kline-McClintock equation:

$$\frac{\Delta C_F}{C_F} = \sqrt{\left(\frac{\Delta F}{F}\right)^2 + 4\left(\frac{\Delta\Omega}{\Omega}\right)^2} \tag{3}$$

Similarly for the power coefficient:

$$C_P = \frac{P}{\rho A \Omega^3 R^3} \tag{4}$$

Applying the Kline-McClintock equation:

$$\frac{\Delta C_P}{C_P} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + 4\left(\frac{\Delta\Omega}{\Omega}\right)^2} \tag{5}$$

According to the experimental data, the average uncertainty for the thrust is approximately 1 %.

For better clarity of the overall uncertainties at *Re* $<1.2\times10^5$, the bias errors dominate the overall uncertainty, whereas for high gradient ranges in particular, the overall uncertainty arises from the repeatability to a great extent.

Table 1 Experimental parameters

Parameters	Value range
D (mm)	400
b(mm)	35
Rotational speed (RPM)	1500 – 2300
Re	0.74×10^5 – 1.13×10^5
M_{tip}	0.09 – 0.14
S/D	1.8, 1.6, 1.4, 1.2, 1.0
φ for every S/D(deg)	(-50,50), (-40,40), (-30,30), (-20,20), (-10,10), (0,0)

3 Results and Discussion

3.1 Wind Effects on Aerodynamic Performance

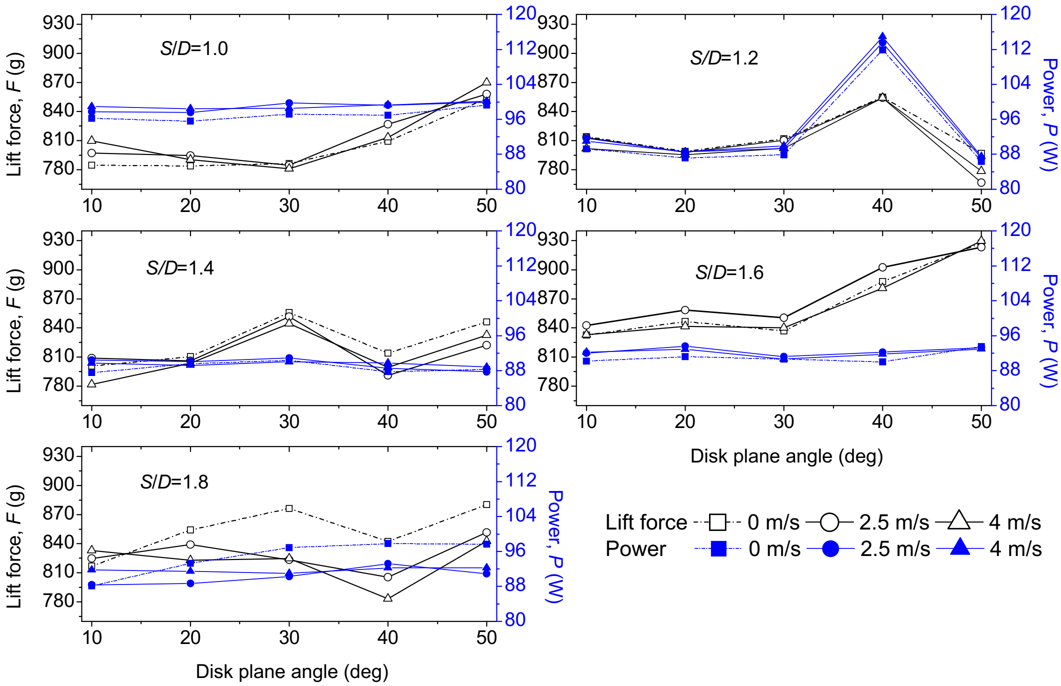
Figure 2 presents the variation of lift force and power with disk plane angle under the work conditions at 2200 RPM. It should be stated that the coordinates for both the lift force and the power are standardized within a certain range. The data obtained from Fig. 2 shows that the interaction between the rotor pairs generates significant impulses for the instantaneous lift and power. The characteristic signature of this impulse can be explained in terms of the wind gust effect. As expected, it can be seen that an increased wind velocity reduces both the lift and the power for the large rotor spacings with a large disk plane angles. Furthermore, interaction between both rotor pairs results in unsteadiness at low-harmonics. As shown in Fig. 2a, for the face-to-face rotor pair, the variation in power consumption with the wind effect is considerably higher than in the case of the 0 m/s. In contrast, the force curve with a wind effect at $S/D = 1.2$ shows very good agreement with S/D =1.4 and 1.8 where the lift force decreases below the case of 0 m/s. In particular, this phenomenon is more obvious for the back-to-back rotor pair presented in Fig. 2b. Thus, it can be concluded that the wake is converted away from the back-to-back rotor pair quickly enough that if and when any instabilities develop in the wake, they are far enough from the rotor to have minimal impact on its inflow and, therefore, its performance. Additionally, there is a significantly more complicated variation for the back-to-back rotor pair than for the face-to-face rotor pair, especially in terms of the power consumption. However, it is interesting to observe that the force increases at $S/D = 1.0$ and 1.6 for the face-to-face rotor pair and at $S/D = 1.0$ for the back-to-back rotor pair. The most likely explanation for this phenomenon is that with a compact configuration, the outflow is strong enough to resist the wind gusts, which has a relatively strong in torsion, generating artificial turbulence that leads to an increase in the flow between the rotors.

For the case of the face-to-face rotor pair at $S/D =$ 1.0, both the lift force of the wind speed at 2.5m/s and 4m/s shared a trend towards increasing compared with the force at the speed of 0 m/s. It should also be noted that the lift force decreases as the angle increases, and the minimum value for the lift force is obtained at 781 g when the disk plane angle φ is 30 deg, after which it begins to increase again. Clearly, considering the wind effect, rotors with this spacing have a greater interaction with their own wake. This heightened interaction is reflected in the lift force.

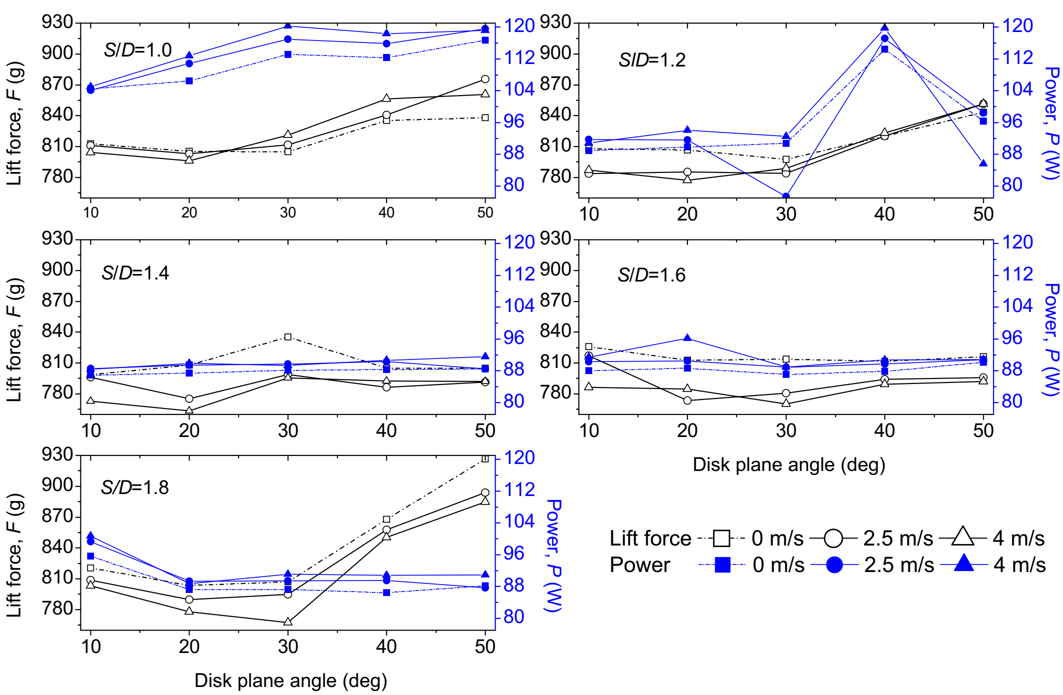
For the case of the face-to-face rotor pair at$S/D =$ 1.6, the lift force with a wind speed at 2.5 m/s shows a considerable increase, with the maximum lift force at 40 deg and the minimum at 50 deg. However, the lift force at 4 m/s shows a performance that is comparable to 0 m/s. Furthermore, the power consumption has a small difference between 2.5 and 4 m/s, while it increases by 3.5 % at 20 deg compared with the power at 0 m/s. The face to face rotor pair has a fair performance as the rotor spacing increases, while the power has an opposite trend, and thus this is not the optimal configuration to resist the wind effect.

For the case of the back-to-back rotor pair, it can be observed that the lift force at 2.5 and 4 m/s increases significantly from 30 to 50 deg at $S/D = 1.0$, while it fails for any other cases. This means that the wind effect on the aerodynamic performance is mainly focused on the back-to-back rotor pair for most of the time when the lift force is below the planar case (φ =0 deg).

Specifically, Figure 3 shows the variation of thrust and power with a rotor spacing ratio under the work conditions at 2200RPM. For the face-to-face rotor pair shown in Fig. 3a, the force increases with a wind speed of 2.5m/s, showing a positive effect compared with a speed of 0m/s. At a somewhat higher speed, the lift force decreases abruptly below the force with a wind speed of 0m/s. This can be explained by the intense wind turbulence at the inflow of the face-to-face rotor pair at high wind speeds. Furthermore, the increased lift force shown for the non-planar rotor pair at 2.5 and 4 m/s occurs mainly within the ranges $1.0<S/D<1.2$ and $1.6<S/D<1.8$ at φ =10 and 20 deg, $1.0<S/D<$ 1.2 and S/D =1.6 at 40 deg, and $S/D = 1.0$ at 50 deg. It is particularly clear that the upwash and downwash are relatively significant for these cases mentioned above, where the unsteadiness increases with increasing wind speed. However, for the back-to-back rotor pair, the variation in lift seems to follow a particular trend. This is in contrast to the face-to-face rotor pair, where the lift increase for the back-to-back rotor pair is limited by the smaller rotor spacing. It can also be noticed that the power always maintains a maximum at $S/D = 1.0$. The exception is at $S/D = 1.2$

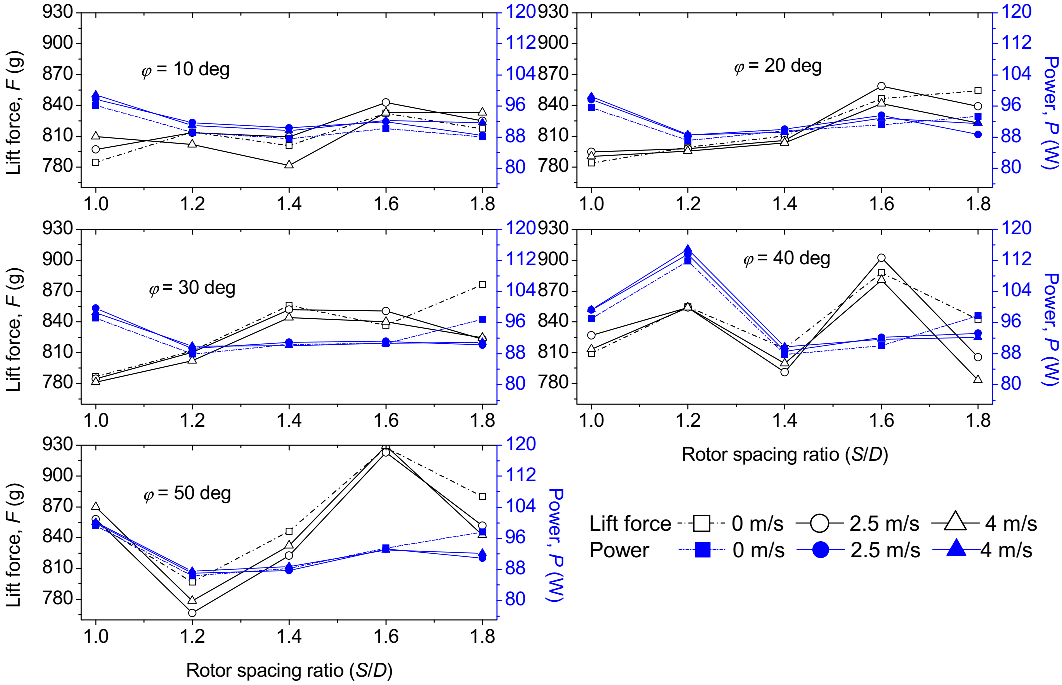


(a) Face-to-face rotor pair

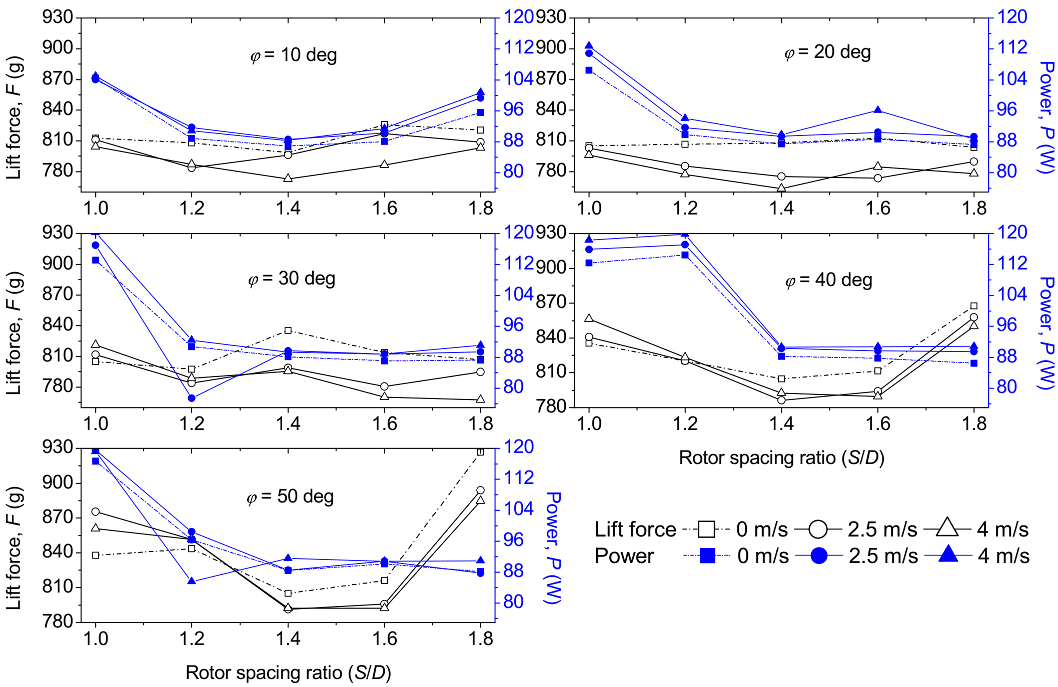


(b) Back-to-back rotor pair

Fig. 2 Variation of thrust and power with disk plane angle



(a) Face-to-face rotor pair



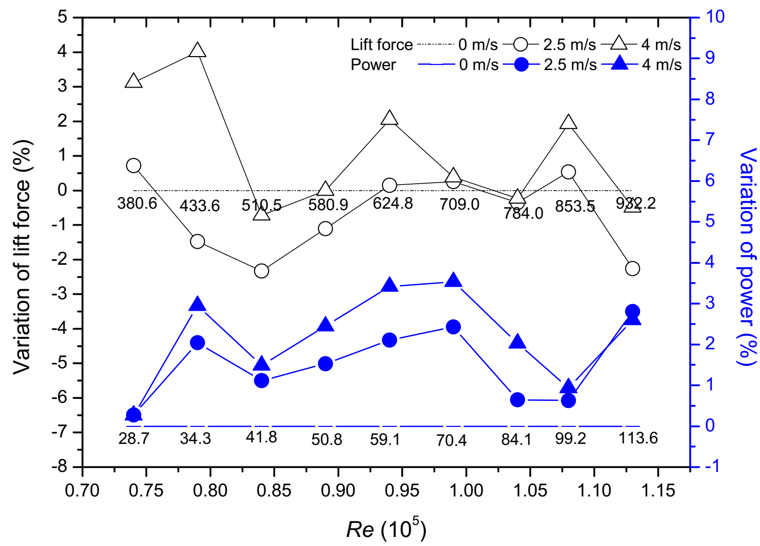
(b) Back-to-back rotor pair

Fig. 3 Variation of thrust and power with rotor spacing and φ =0 deg, where the maximal variation is 16 %, although the power consumption shares the maximum value and then decreases abruptly. For the back-to-back rotor pair shown in Fig. 3b, the increased lift force at 2.5 and 4 m/s occurs mainly for S/D = 1.0 at 10, 20 and 30 deg, and 1.0<S/D < 1.2 at 40 and 50 deg. The reason for these differences is due to the vortex impingement on the back-to-back rotor pair being more prominent and at times larger than the peak effect on the face-to-face rotor pair. This suggests that in contrast to the face-to-face rotor pair, the wind effect for the back-to-back rotor pair can play a significant role in reducing the unsteadiness when the rotor spacing is small.

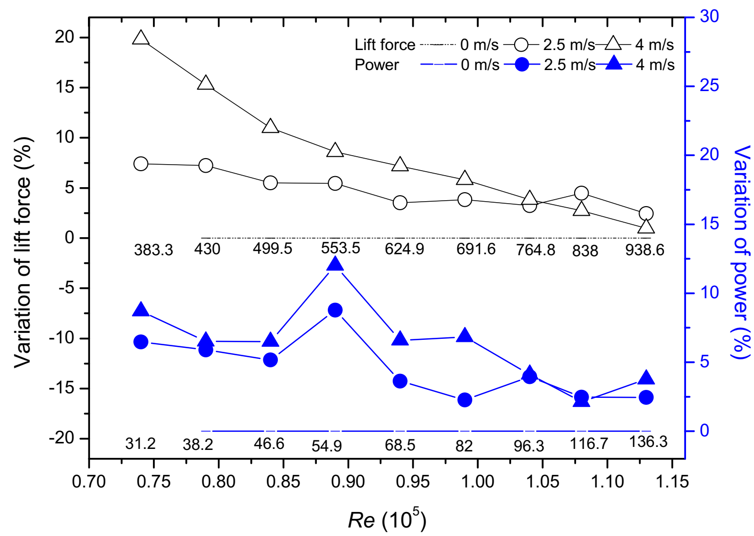
3.2 Wind Effect on Low *Re*

Preliminary investigations on the aerodynamic performance have shown that the wind turbulence increases the lift force and power consumption by altering the inflow and the outflow of the rotor pairs. However, the effect of the wind on the aerodynamics for such low *Re*

Fig. 4 Variation of thrust and power with Re (S/D=1.0, φ = 50 deg)



(a) Face-to-face rotor pair



(b) Back-to-back rotor pair

environments is still unknown. Therefore, any attempt to optimize the configuration must consider only the average aerodynamic operating environment. To highlight this further, Figures 4 and 5 present the average performance with a large disk plane angle and small spacing ratio (S/D =1.0, φ =50 deg), and the performance with small disk plane angle and large spacing ratio (S/D =1.8, φ =10 deg), respectively.

Figure 4 shows the variation curves of the lift force and power for a non-planar rotor pair with uniform flow at 2.5 and 4 m/s as a function of the external turbulence acting on both rotor pairs that have been investigated in the present work, together with the performance curve at 0 m/s for S/D =1.0 with φ =50 deg. From the data shown in this figure, it can be observed that higher wind speeds result in higher increase in the lift force.

For the face to face rotor pair showed in the Fig. 4a, the lift force at 4 m/s is considerably higher than for the case of 0 m/s, whereas most of time, the variation at 2.5 m/s is below the case of 0 m/s. As *Re* increases, there is a sharp drop in lift force observed

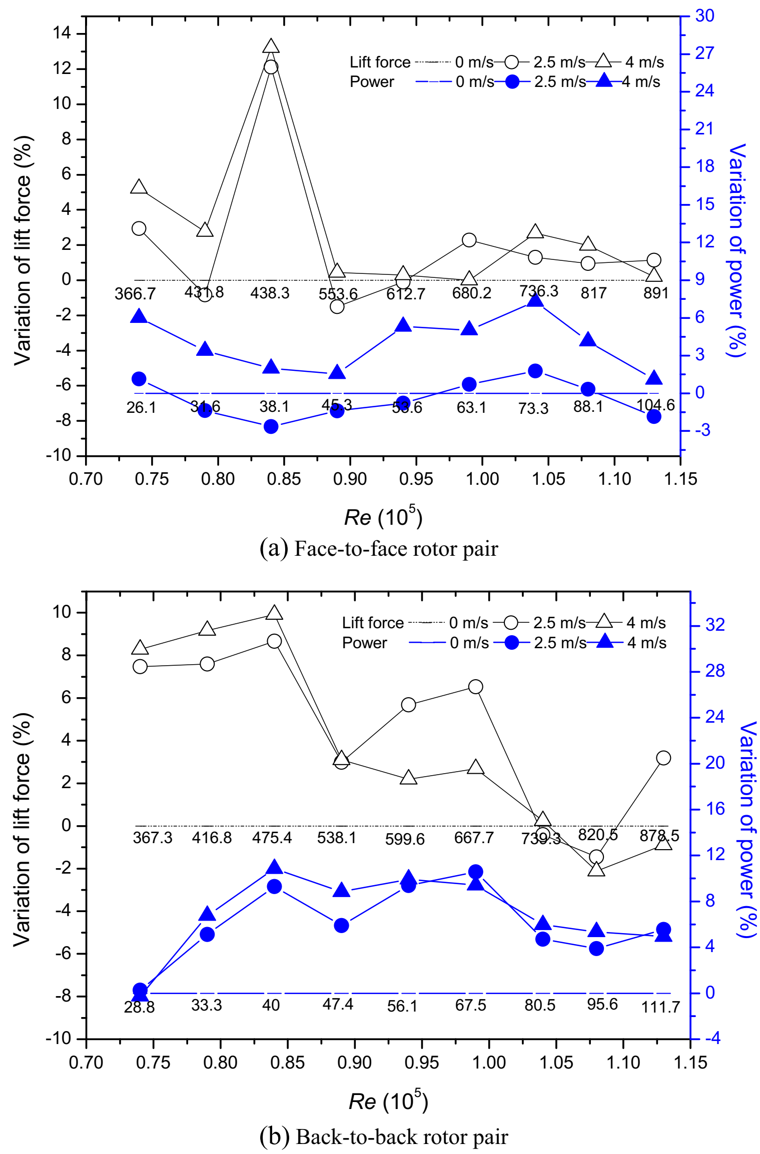
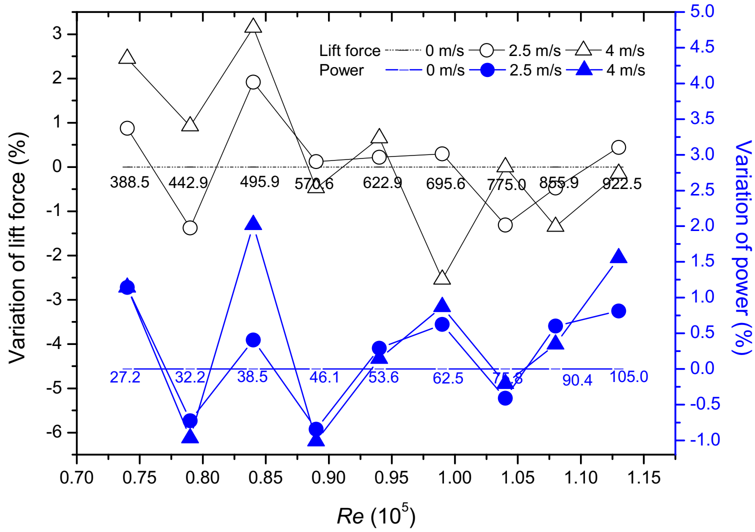


Fig. 5 Variation of thrust and power with Re (S/D=1.8, φ = 10 deg)

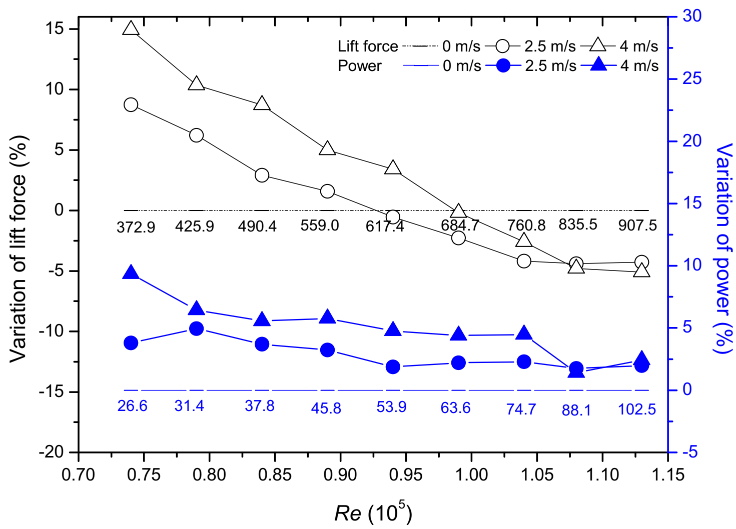
over the range from 0.79×10^5 to 0.84×10^5, suggesting the effect of air viscosity. Furthermore, the variations curves for the power show good agreement with the tendency for variation of the lift force, when both of the maximum are around 4 %. These results, which take into account the increase in the lift force at 4m/s, have better improvements in performance than at 2.5m/s, and clearly indicate the benefits of the face-to-face rotor pair at a higher wind speeds.

For the back-to-back rotor pair shown in Fig. 4b, the most interesting observation is that both the force and power have higher value than at 0 m/s across the whole *Re* range, and the maximum increase in lift and power is 20 % and 12 %, respectively. This is due to the wind effect increasing the outflow through the rotor, which reduces the interference between rotors. However, at higher *Re* ranging from 0.74×10^5 to 1.73×10^5, the lift force decreases linearly with *Re*. Thus, it can be concluded that the interference between the rotors becomes dominated by the wind effect, which has a negative effect on the performance.

Figure 5 also presents the variation curves for the lift force and power at 2.5 and 4 m/s with *Re* for both rotor pairs at S/D =1.8 with φ =10 deg, together



(a) Face-to-face rotor pair



(b) Back-to-back rotor pair

Fig. 6 Variation of thrust and power with Re (S/D=1.4, $\varphi = 30$ deg) with the performance curve at 0 m/s. For the face-to-face rotor pair depicted in Fig. 5a, compared to the performance shown in Fig. 4a, we can see that the power decreases over the *Re* range from 0.75×10^5 to 0.9×10^5, accompanied by a lift increase, which shows a good wind resistance. It is not entirely surprising that the performance of the back-to-back rotor pair shown in Fig. 5(b presents a similar trend to Fig. 4b, where the proven performance is characterized by a larger lift increase and a smaller power increase.

Additionally, Figure 6 presents the variation curves for the lift force and the power at 2.5 and 4 m/s with the *Re* for both rotor pairs with combined configuration with a medium rotor spacing and disk plane angle ($S/D = 1.4$, $\varphi = 30$ deg). It is interesting to note that both rotor pairs show a similar trend to Fig. 4 ($S/D = 1.0$ with $\varphi = 50$ deg). However, for both rotor pairs, the lift falls below the curve at 0m/s in the *Re* range from 1×10^5 to 1.15×10^5 although the power still increases, which shows a poor performance as compared with smaller rotor spacing and a larger disk plane angle. This implies that there is higher interference with the induced flow due to the increased rotor spacing and the decreased disk plane angle which cause the poor performance.

4 Conclusions

In this study, aerodynamic force and power measurements were taken for two non-planar rotor pairs in order to further understand the aerodynamic complexities due to the wind effect and to attempt to obtain an improved configuration for the non-planar rotor pairs that can maximize the performance in hover. The knowledge obtained from this study was used to estimate the improvements in lifting performance that may be possible when a vehicle is operating at hover with wind gust. Furthermore, it was also shown that several different combinations of rotor spacing and disk plane angles could provide comparable levels of aerodynamic efficiency with good wind resistance. The following are the specific conclusions that were drawn from this study:

(1) Both the non-planar rotor pairs showed improvements in performance as the wind speed increased, that is, higher thrusts and lower power requirements, particularly, where a large disk plane angle was combined with a small spacing ratio or a small disk plane angle was combined with a large spacing ratio. For these combinations, the maximum increases in lift force and power consumption reached 20 % and 12 %, respectively.

(2) When working at 2200 RPM, a proper combination of rotor spacing and disk plane angle increased the positive effects of the wind, and the lift force increased considerably while maintaining reasonable power consumption. However, this was not effective for both the face-to-face rotor pair and back-to-back rotor pair at the same time. The reason for this is that when comparing the two non-planar rotor pairs, the performance is affected in two ways. First, there is a reciprocal effect through the slipstream of the two rotors; and second, there is wind turbulence that acts on the operating conditions.

For the face-to-face rotor pair, the lift force was found to be sensitive to wind turbulence, although it was still much improved. For the back-to-back rotor pair, negative values were seen for the lift force at 2.5 and 4 m/s where it went below the 0 m/s. For SUAVs with this type of non-planar rotor pair, efficient design of the rotor system depends on the performance of the back-to-back rotor pair.

(3) There was much improved performance of the back-to-back rotor pair seen at $S/D = 1.0$ with $\varphi = 50$ deg, confirming this configuration for the rotor system to increase the lift force and maintain stable power consumption. This can be explained by being due to the stability with a condensed rotor spacing and strong flow interaction with a large disk plane.

(4) For the wind speed at 2.5 m/s, the performance of the rotor pair is improved and stable with good resistance in the ranges $1.0 \leq S/D \leq 1.8$ and $0 \leq \varphi \leq 50$ deg, whereas the performance get worse at 4 m/s where the lift force is seen to decrease.

(5) For a low *Re* environment ranging from 0.74×10^5 to 1.73×10^5, the experimental results showed an increased tendency for the lift and an increased tendency for the wind resistance as *Re* increased, both at 2.5 and 4 m/s, where the power increase also showed considerable agreement with the force curve. Furthermore, the improved

performance for the back-to-back rotor pair is mainly focused on the power reduction while for the face-to-face rotor pair is characterized by the significantly increased lift force.

Finally, although only limited range of the measurement parameters and *Re* were investigated, further studies will focus on a more in-depth examination of the various design tradeoffs in such a non-planar concept.

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