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An experimental investigation on aerodynamic performance of a coaxial rotor system with different rotor spacing and wind speed

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ABSTRACT

The present work analyses the aerodynamic complexities involved in the optimization of a coaxial rotor system in an attempt to maximize its performance in hover flight. Performance measurements (thrust and power consumption) of the system and the influence of design parameters (rotor spacing and wind speed) on performance are obtained with the aerodynamic momentum theory and the hover test stand. Combined with the error analysis, the systematic testing of isolated rotor (top rotor and bottom rotor) is performed to give a performance baseline for the coaxial rotor system. Rotor spacing experiments indicated that the aerodynamic interference with different spacing generated different thrust and powers in hover flight, and the performance was indeed improved with a proper spacing as compared to the large rotor. Furthermore, the effect of the wind speed on the rotor performance is also studied as the external disturbance to help study the aerodynamic performance of the coaxial rotor system. Test results showed that the horizontal wind played a dominant role on the rotor aerodynamics while the effect of the vertical wind is relatively stable.

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1. Introduction

In the last few decades, the Micro-aerial vehicles (MAVs) in multi-rotary-wing configuration have generated great interest in the rotor aerodynamics. Due to the unique hovering capability and a small rotor diameter without a separate anti-torque system, these kinds of vehicles are specially suited to perform missions considered tough, dirty, or dangerous [1,3]. Although the development of the rotor aerodynamics of the micro-scale rotorcraft was hobbled by technology insufficiencies through most of the 20th century, the efforts were focused on the computational and experimental researches to overcome the problem of poor aerodynamic performance resulted by the low Reynolds (often below 10^5 based on characteristic chord dimensions) for the MAVs, where the viscous effects tend to increase viscous losses and adversely affect lifting surface behavior [2]. As a result, the particular challenge in improving the aerodynamic performance lies in overcoming the various aerodynamic problems associated with low Reynolds number flight, which generally manifest as lower efficiencies and higher power consumption [1].

The counter-rotating coaxial rotor platform, as one of the most notable advantages, requires no separate means of anti-torque. For the same vehicle weight and disk loading, the coaxial system has another advantage in terms of vehicle compactness. However, the main difficulty to achieve a better performance with the coaxial system comes from the large hover power requirements and the thrust changes which reduce the hover efficiency and it must be carefully addressed [4].

The rotorcraft mentioned in this paper is largely motivated by the development of a coaxial MAV. It is a new configuration with six coaxial rotor systems, where the scale and the aerodynamics of every single coaxial rotor system are unique to the whole MAV. The main areas of the present investigation are focused on rotor aerodynamics of the full-scale single and coaxial rotor system affected by different rotor spacing and wind speed. Generally, as one of the design parameters in coaxial rotor system, rotor spacing is required to reduce the aerodynamic interference and avoid blade collisions of two rotors. Compared with the larger scale rotorcraft where the change of the rotor spacing is relatively small, the design of the rotor spacing is more important to study the rotor aerodynamics in MAVs [5]. Considering the tough environment, the wind speed, as another factor to affect the hover flight, is also considered as the external disturbance to observe the aerodynamic performance of the coaxial rotor system.

Many efforts have been made to calculate the thrust and power requirements by modeling coaxial rotors, however, most rotors are relatively large and most of the algorithms need empirical models of the wake geometry. Recently, Syal used simple momentum theory and Harrington Rotor (R is 3810 mm) to optimize a coaxial rotor system. He found that the performance of both the top and the bottom rotors degraded due to the interference effects between the

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Nomenclature

C_T	thrust coefficient	PL	power loading (g/W)
T	thrust (g)	Q	torque (Nm)
ρ	air density (kg/m^3)	Re	Reynolds number
A	area of the rotor (m^2)	M	mach number
Ω	rotational speed (r/min)	R	radius of the rotor (mm)
C_p	power coefficient	h	rotor spacing (mm)
P	power (W)		

two rotors, and the increasing rotor spacing could reduce these effects [6]. Bohorquez has performed experimental measurements on a micro-coaxial air vehicle (R is 172 mm) at torque equilibrium for different rotor spacing in the presence of parametric uncertainties. He considered that the upper rotor was only affected by the lower one at spacings larger than 35% of the rotor radius [7]. Lakshminarayan and Baeder attempted to develop and validate a high resolution computational platform that can be used to investigate various aerodynamic challenges associated with the current coaxial rotor MAV configurations with different rotor spacing on the rotor flow-field [8]. More experimental studies combined with wind tunnels have been conducted since the dawn of the 20th Century. However, the only available experimental data could be obtained from model testing intended for full-scale design at Re of one million and above. The main contribution of the experimental study on coaxial rotor aerodynamics is made by Coleman, who presented a broad perspective of experimental data and analysis that related to rotor separation distance, load sharing between the rotors [9]. More recent experimental work has been conducted by McAlister et al., trying to confirm the difficulties in modeling coaxial rotor performance and in assessing the hover performance of a three-bladed sub-scale tilt rotor with varying rotor spacing distance and ground effect [10].

Based on the aerodynamic performance of the coaxial rotor systems provided by the above authors, the higher induced losses and aerodynamically lower efficiency were noticed. However, there are two issues that are worth pointing out. On the one hand, for the most researches, only the model scale rotors were tested, and on the other hand, external disturbances and measurement uncertainties of the coaxial rotor system are not considered.

In this paper, a wide range of the rotor spacing and wind speed are introduced to maximize the aerodynamic performance of the coaxial rotor system with a new novel rotor configuration, which is an improvement to fulfill the experimental investigation on aerodynamics of MAVs. Combined with the low Reynolds number and the limited experimental data of previous work, the main idea is to figure out the best configuration and performance of this 12-rotor MAV with a designed hover test stand.

The modeling of the coaxial rotor system [7] is presented in Fig. 1. Obviously, the boundary of the flow-flied is mainly affected by the rotor spacing between the two rotors. Definitions of the related coefficients are as follows:

Thrust coefficient:

$$C_T = \frac{T}{\rho A \Omega^2 R^2} \quad (1)$$

Power coefficient:

$$C_P = \frac{P}{\rho A \Omega^3 R^3} = \frac{Q\Omega}{\rho A \Omega^3 R^3} = \frac{Q}{\rho A \Omega^2 R^3} \quad (2)$$

Power loading (PL):

$$PL = \frac{C_T}{\Omega R C_P} = \frac{T}{Q\Omega} \quad (3)$$

2. Experiments

2.1. Experiment setup

The hover efficiency affected by the coaxial rotor spacing and the wind speed are crucial for the implementation of a coaxial MAV. This section describes the experimental setup used for evaluating the performance of the coaxial rotor system. In order to experimentally measure the aerodynamic performance, a test stand was developed as follows.

The experiments were preceded with a hovering coaxial system having two 2-bladed rotors. The rotor radius and the average blade chord of the top and bottom rotors are 200 mm and 35 mm, respectively. Based on the performance metrics of the coaxial system [7], it was obvious that three physical quantities are required to identify the rotor system performance: rotational speed, system thrust and power consumption.

The sketch of the test stand is shown in Fig. 2. The rotor system was fixed inversely at the height of 1.5 m to avoid the in-ground effect on the measurements, and the whole system could rotate

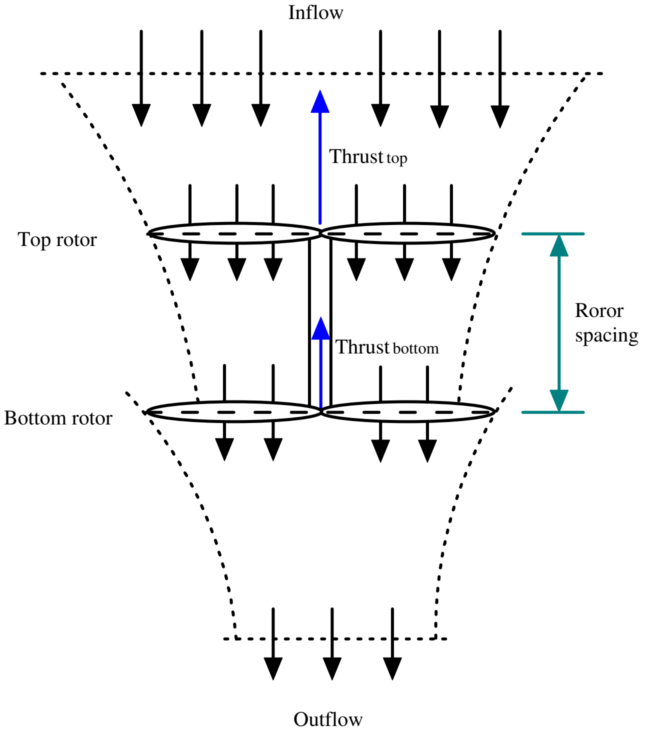

Fig. 1. Flow model of a coaxial rotor system.

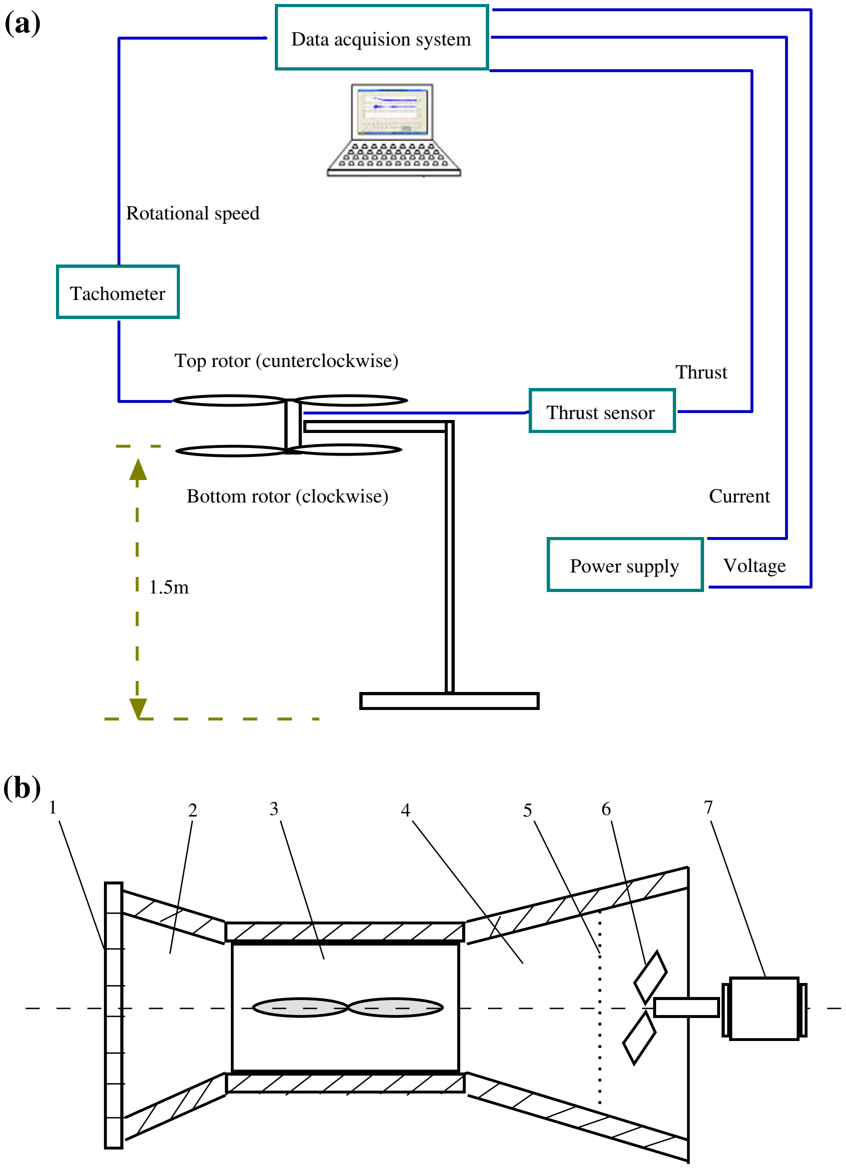

Fig. 2. Experimental setup. (a) Rotor spacing test. (1) Perforated distribution plate, (2) contraction section, (3) test section, (4) expansion section, (5) safety net, (6) fan, and (7) DC motor. (b) Wind tunnel test.

freely. Thrust was measured by the weighing sensor (type: CZL605, accuracy: 0.02% F.S), which was placed directly under the rotor shaft, while the rotational speed was measured by a tachometer (type: DT-2234C+, accuracy: ±(0.05% + 1 d)). Additionally, the voltage and current of the rotor system were also measured to obtain the power consumption. In this setting, there were no extra hinges or bearings. So the input signals including the coaxial thrust, rotational speed of top rotor and bottom rotor, current and voltage were sent to the data acquisition system. The characteristics of the measurement system are as follows: (1) rotors were mounted inverted without the ground effect and (2) no redundant parts were involved in the measurement system, and the independent transmission of each rotor decreased the introduced error.

In these conditions, the rotor spacing can be varied from a minimum distance. Considering the mount of the motor between the rotors and the whole structure of this MAV, the minimum was confirmed as 64 mm ($h = 0.32R$) and the maximum of the separation was 150 mm ($h = 0.75R$). By combining the information provided by this experimental setup, the obtained rotation speed of each rotor, electric current, voltage, the voltage variation of the weighing sensor can be processed by the data acquisition system. The following series of tests were performed: (1) validation test for the characters of the isolated rotor; (2) rotor spacing tests of the coaxial rotor system; and (3) wind tunnel tests of the coaxial rotor system.

2.2. Rotor spacing test

In the rotor spacing test, the top rotor was counterclockwise and the bottom rotor was clockwise. Experiments were conducted by changing the rotational speed (RPM) roughly arrange from 1300 RMP to 2600 RPM, correspondingly, the tip Reynolds number varied from 0.64×10^5 to 1.28×10^5 and the tip Mach number ranged from 0.08 to 0.16. For a lower RPM, the thrust of the rotor blade was more sensitive to the viscous effects resulted by the lower Reynolds number. Besides, the variation of current and voltage resulted by the thrust were also obtained and recorded by the data acquisition system. With respect to the effect of the rotor spacing case, the isolated top and bottom rotor were tested to establish the comparable performance. Considering the adjustment of separation distance, seven different normalized rotor spacings $h = 0.32R$, $0.39R$, $0.45R$, $0.52R$, $0.58R$, $0.65R$ and $0.75R$ were studied respectively.

2.3. Wind tunnel test

With respect to the future control actions, the wind tunnel test was required to accomplish the effect of the external disturbance on aerodynamic performance in hover flight or at least to help the piloting of the vehicle, with high maneuverability and robustness.

Considering that the wind speed is usually less than 5 m/s in the work environment, the low speed wind tunnel was chosen to produce the even wind which mainly included four sections: the contraction section, test section, expansion section and the power installation. To eliminate any maelstrom and produce the stable airflow, the perforated distribution plate was equipped at the front of the contraction section. The entire rotor system was placed at the test section where the size is 1 m × 1.5 m. To slowdown the airflow and decrease the energy loss, the expansion section was considered. The rotor system was mounted the same way as in the spacing test, the horizontal wind with three different velocities (0 m/s, 2.5 m/s and 4 m/s) and the vertical wind with two different velocities (2.5 m/s and 4.5 m/s) were acted on the coaxial rotor system respectively. Additionally, the aerodynamic power required by the coaxial rotor system and the thrust were measured and recorded in the data acquisition system when the rotor system was constantly affected by these external disturbances.

3. Error analyses

Based on the experimental setup mentioned in Section 2, two main error sources were introduced: the measurement errors resulted by the tachometer (rotational speed) and the thrust sensor (voltage variation). Generally speaking, error of the tachometer was related to the number of magnets in the motor. Currently, 24 magnets were used in the individual motor, so there was an uncertainty of 1/24 revolution for every sample of the rotor. While the error resulted by the thrust was proportional to the square of the rotational speed, for a given rotational speed range, by applying 'Kline – McClintock equation', the uncertainty of the thrust [11] was calculated as follows:

$$\Delta C_T = \sqrt{\left(\frac{C_T}{T}\cdot \Delta T\right)^2 + \left(\frac{-2C_T}{\Omega}\cdot \Delta\Omega\right)^2} \tag{4}$$

Finally,

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

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

It is similarly for the power coefficient and the power loading (PL) related with thrust.

For the power coefficient:

$$\frac{\Delta C_P}{C_P} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + 4\left(\frac{\Delta\Omega}{\Omega}\right)^2} \tag{6}$$

For the power loading (PL):

$$\frac{\Delta PL}{PL} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta\Omega}{\Omega}\right)^2} \tag{7}$$

According to the equations mentioned above, the uncertainties of the power coefficient and power loading are 1% and 1.5%, respectively.

4. Results and discussion

4.1. Rotor spacing

For the coaxial rotor system, Rotor spacing was increased from 64 mm to 150 mm ($0.32R \leqslant h \leqslant 0.75R$) in these tests. Thrust vs. the power consumption at different spacing is showed in Fig. 3a. It is clear that the rotor thrust increases with the power consumption. Obviously, the thrust at 129 mm decreased when the power consumption is greater than 60 W. Similar trend can be seen at 90 mm, 103 mm, 116 mm and 150 mm. Also shown in Fig. 3b is that the thrust of the isolated top and bottom rotor increased with the power requirement. As expected, compared with the result of the isolated single rotor presented in Fig. 3b, the thrust of the coaxial rotor system increases faster than the single rotor though the tendency is not clear when the power consumption is lower than 30 W. Additionally, it is also evident that the coaxial thrust reduced as compared with the total thrust of the isolated top and bottom rotor. The reason for the differences is explained by the different location of the impingement of the top rotor vortex on the bottom rotor.

As the representation, thrust variation along with the power consumption of the rotor spacing at 103 mm is selected, plotted with 64 mm, 77 mm with a larger thrust, and 129 mm with a different variation are showed in Fig. 4a. The total coaxial system

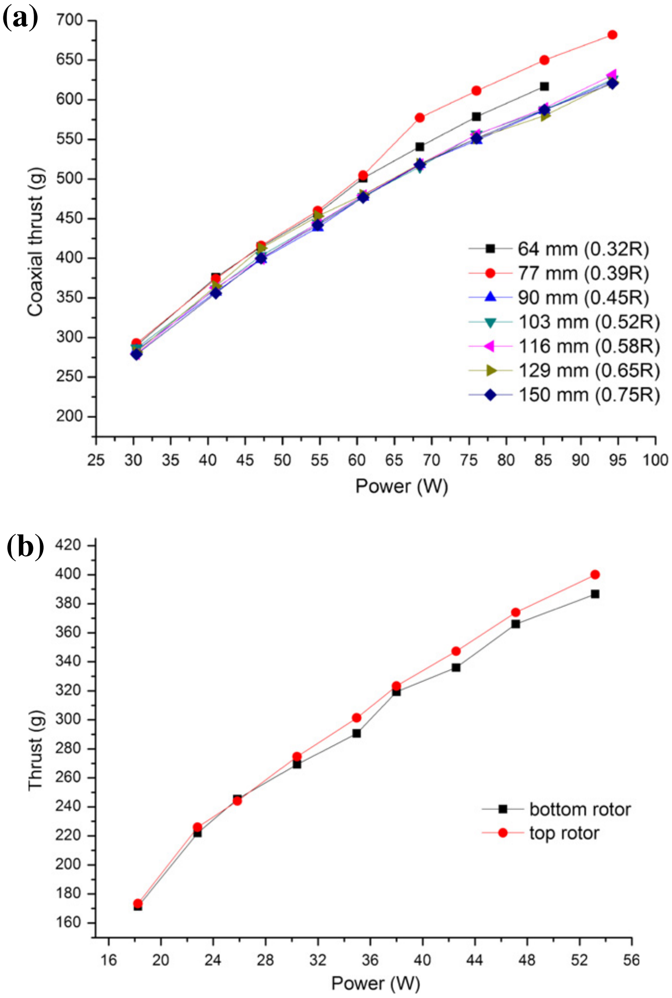

Fig. 3. Average thrust vs. power consumption. (a) Average thrust vs. power consumption of a coaxial rotor system at seven different spacing. (b) Experimental thrust vs. power consumption of single rotor.

thrust is well described at all rotor spacing. With higher power consumption, the effect of the rotor spacing on thrust is showed in Fig. 4b. It seems that the rotor thrusts approach a constant value at very large rotor spacing, and the absolute value of the fluctuation decreases with increasing rotor spacing. Note that, the rotor spacing at 64 mm and 77 mm suffered a larger thrust which is probably resulted by the turbulent flow-field between the two rotors [12]. To compare with the precious work, the thrust at 0.268*R*, 0.446*R* and 0.625*R* ($R = 112$ mm) simulated by Lakshminarayan and Baeder [8] is consistent with the experimental result.

Fig. 5 shows the comparison variation of coaxial thrust as function of different rotor spacing at 1580 RPM, 2000 RPM and 2400 RPM, and error bars extend for three standard deviations. It can be clearly obtained that the higher rotor spacing does not bring the larger thrust, while the thrust reaches a constant. However surprisingly, the thrust at rotor spacing between 60 mm and 80 mm achieves a better performance. Eventually, thrust suffers minor changes beyond a certain value, which is consistent with the conclusion conducted in Ref. [13]. In this case, the rotor separation is 130 mm ($h = 0.65R$).

To maximize its power loading and make a quantitative comparison of the results as Sunada addressed in Ref. [14], for these seven spacings, the aerodynamic characteristics (including average thrust, torque and power loading) correspond to typical RPM is depicted in Fig. 6, and the error bars cover three standard deviations. The total thrust and the torque of the system are seen to increase fairly constant with the RPM, and an increase in RPM almost always results in a decrease in the power loading.

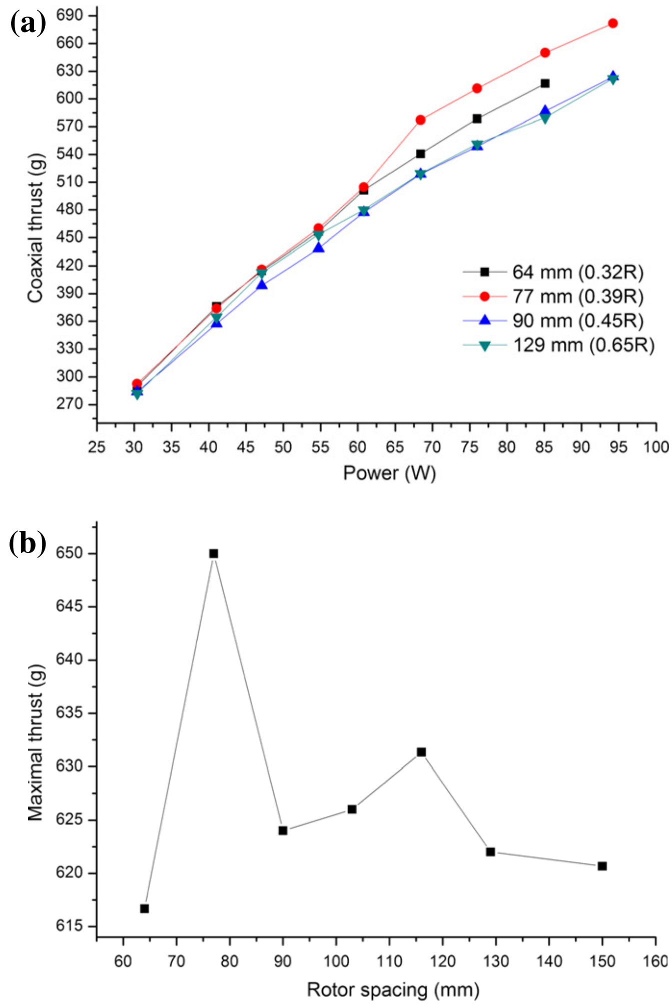

Fig. 4. Average thrust vs. power consumption of typical rotor spacing. (a) Variation tendency of the typical rotor spacings. (b) The maximal thrust at different seven rotor spacing.

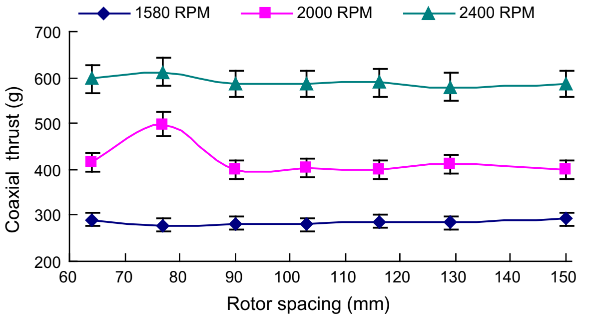

Fig. 5. Coaxial thrust vs. normalized rotor spacing at typical RPM.

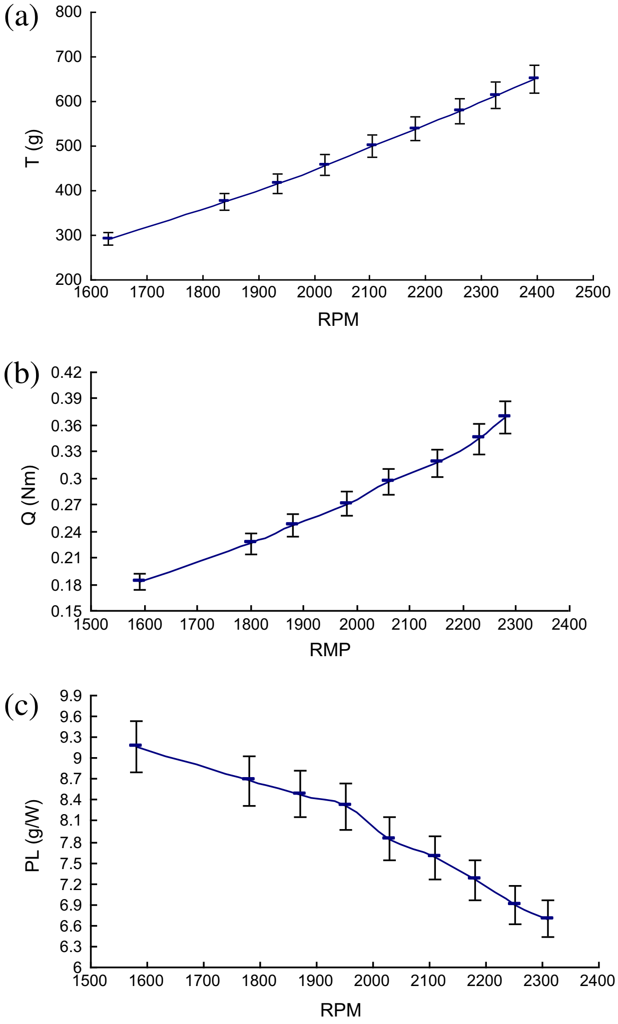

Fig. 6. Aerodynamic characteristics vs. RPM. (a) Average thrust vs. RPM. (b) Torque vs. RPM. (c) Power loading (PL) vs. RPM.

4.2. Wind tunnel test

The horizontal wind test result and the vertical test result are showed in Fig. 7. The thrust has a tendency to increase with the power consumption. In order to make a quantitative comparison of the results attained by these two instances, the wind speed at

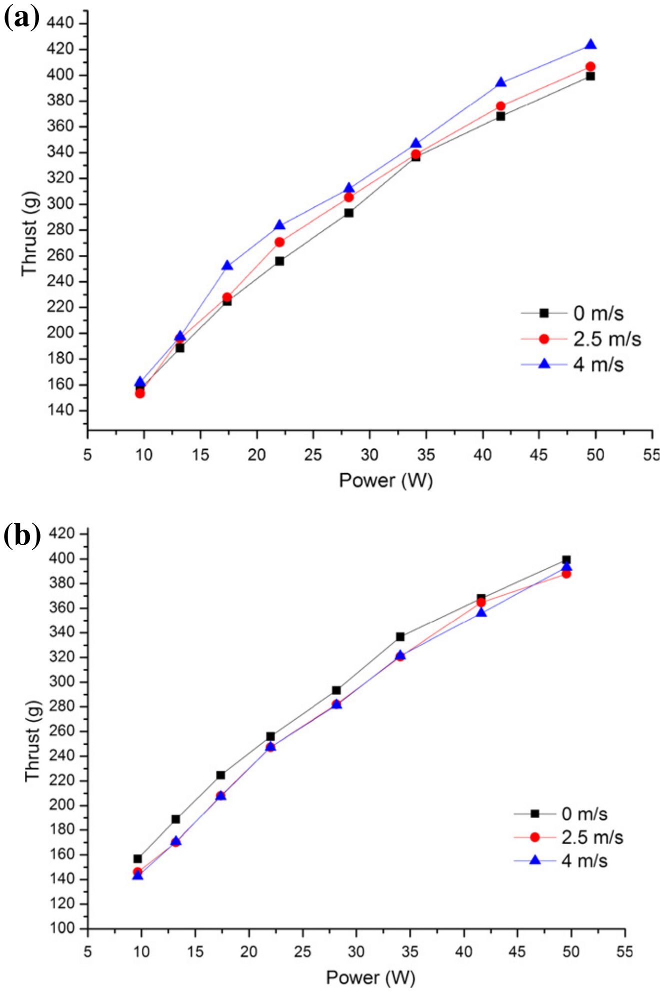

Fig. 7. Thrust vs. power consumption of wind tunnel test results. (a) Horizontal wind tests. (b) Vertical wind tests.

0 m/s is showed in both test result. For the horizontal wind test, as presented in Fig. 7a, the higher thrust is resulted by the higher horizontal wind speed, however, the opposite trend is showed in the vertical wind test presented in Fig. 7b. The reason for this phenomenon is probably because of the cancellation between the vertical wind and the system thrust. Additionally, the percentile variation of thrust measured at the highest thrust is less than 4% at the horizontal direction while the percentile is less than 1% at the vertical direction. In this case, the effect of horizontal wind on the thrust is much more obvious than the effect of the vertical wind, and the effect of the vertical wind is relatively more stable. It is interesting to note that the effect of the wind speed on a coaxial rotor system in this case is unique, and it is useful to complete the control strategy in the further studies.

5. Conclusions

MAVs are an emerging technology that can provide an inexpensive and expendable platform to a wide array of missions where larger vehicles are impractical to transport or operate. However, the capabilities of current rotor system fall short of various mission requirements due to limitations arising from aerodynamic issues. In the meantime, differences in blade geometries, rotational speed, Reynolds number, and power loadings affect the inflow distribution, making very difficult to draw a general conclusion about how to maximize the aerodynamic performance of a coaxial rotor system. However, combined with a new configuration mentioned in this paper, the present study has attempted to further analyze the experimental error of counter-rotating coaxial rotors, and to figure out how to make a profitable rotor spacing to maximize the aerodynamic performance of a coaxial rotor system. Furthermore, the wind tunnel tests were conducted to study the effects of changes in both horizontal and vertical direction as the external disturbance. The study showed that the performance of the coaxial rotor system can indeed be increased by changing the rotor spacing, and the effect of the horizontal wind on rotor aerodynamics is more obvious.

The following are the specific conclusions drawn on the present study on micro-scale coaxial rotor system with the new configuration:

(1) Based on the limited experimental measurements, error analysis was performed and showed reasonably good agreement with the measurements. The error of the measurement system decreased along with the rotational speed, more over, uncertainties of the thrust, power efficient and power loading were obtained through the theoretical error analysis, and the maximum was less than 2%.
(2) Parametric studies were conducted to analyze the effects of changes in rotor spacing. It is clear that coaxial thrust increases with the rotor spacing, while the thrust stabilizes when the spacing reaches a certain value, which is consistent with the experimental result conducted by Sunada et al. [14]. Combined with the experimental results of these seven rotor spacings, 77 mm is more suitable for the rotor system to achieve a better aerodynamic performance with a minimum interference between the two rotors.
(3) The role of the RPM is important to avoid any induced error resulted by the thrust and torque. The coaxial tests performed covered rotational speeds roughly between 1300 and 2600 RPM which are sufficient to implement the measurement error and a higher RPM achieve a better performance of the rotor aerodynamics.
(4) The wind tunnel test shows that the effect of the wind speed on the rotor performance mainly existed in the horizontal wind, where the thrust and power consumption increased with the wind speed, while the effect of the vertical wind is relatively stable, where the thrust and power consumption surprisingly decreased with the wind speed because of the interference between the two rotors.

Finally, future work will involve the implementation of this experimental investigation in the full rotor system of this MAV, including: (1) measuring the thrust and torque independently on each rotor is a much more desirable option. In this case, the thrust sharing and the separate power requirements of the upper and lower rotors could be obtained directly and (2) surface pressure measurements and flow field measurements may explain the aerodynamic interactions much better and give a more complete understanding of the aerodynamic performance of coaxial rotor system.

Acknowledgements

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