Aerodynamic Characteristics of a Hex-Rotor MAV With Three Coaxial Rotors in Hover

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ABSTRACT In order to study the aerodynamic characteristics of a Hex-rotor micro aerial vehicle (MAV) with different rotor spacing, both experiments and numerical simulations are performed in this paper. First of all, a series of aerodynamic parameters to characterize the hover performance of the Hex-rotor MAV are analyzed theoretically. Secondly, tests on the Hex-rotor MAV with different rotor spacing ratios \((i = 0.5, 0.56, 0.63, 0.71, 0.83, 1.00)\) is presented in detail. The thrust and power of the Hex-rotor MAV are obtained from the self-designed test platform. In the meanwhile, pressure and velocity distribution of the Hex-rotor MAV are obtained by Computational Fluid Dynamics (CFD) simulation. The results show that the aerodynamic performance of the Hex-rotor MAV is varied with the rotor spacing. Specifically, the rotor interference is inclined to improve the aerodynamic performance of the Hex-rotor MAV with the proper rotor spacing. Owing to the increase of rotor spacing, the interactions between rotors are weakening gradually. In addition, the uniformity of velocity distribution, the stability of downwash distribution and the integrity of vortex are the necessary conditions for a larger thrust of the Hex-rotor MAV. Finally, combined with the test and simulation results, it is also found that there is larger thrust characterized with better aerodynamic performance at \(i = 0.63\), which is assumed as the best rotor arrangement of the Hex-rotor MAV. Especially for \(Re = 1.16 \times 10^5\), the thrust increases by 6.09\%, and the hover efficiency increases by about 9.17\% in general.

INDEX TERMS Hex-rotor MAV, aerodynamic performance, rotor spacing, rotor arrangement, hover efficiency.

I. INTRODUCTION

More recently, a Hex-rotor micro aerial vehicle (MAV) composed of three coaxial rotors is emerged with a strong potential in both civil and military. The connection between adjacent coaxial rotors forms an equilateral triangle, which will make the weight of the whole machine relatively concentrated near the center of mass of the MAV. This kind of coaxial multi-rotor MAV has the characteristics of compact structure, outstanding load capacity, and strong controllability of yaw [1]–[5]. The Hex-rotor configuration is mechanically simple without redundancy of linkages for rotor actuation. Also, a relatively longer hover time makes it a good candidate for human and transportation, inspection, and military [6], [7]. Armando [8]–[10] et al. proposed the dynamic model of the Hex-rotor MAV, and performed a stability analysis to ensure the stability of the entire aircraft system. Yoo [11] et al. introduced the two designs of single Tri-Rotor MAV and coaxial Tri-Rotor MAV, and put forward the control strategy for each Tri-Rotor type. In addition, Thomas et al. conducted in-depth research on the influence of low Reynolds number and aspect ratio on the structure and aerodynamic performance of aircraft [12], [13]. Theodor [14] et al. performed autonomous flights with the Hex-rotor aircraft in a wind tunnel to verify the method of aerodynamics acting on the aircraft in flight and estimate the aerodynamic power of the propeller, and eventually produced a fully operational flying anemometer; Ramasamy et al. [15] conducted particle image velocimetry (PIV) flow field test on a self-designed test platform for the
aerodynamic performance of a single rotor, and obtained the wake boundary results and images of a single rotor in hover at low Reynolds number (Re).

Currently, the research of the Hex-rotor MAV is only focused on the control strategy and trajectory planning. There are few studies on the aerodynamic effect between the rotors of Hex-rotor MAV. Thus, this paper tackles a structural optimization problem of Hex-rotors with coaxial rotors applicable to a wider class. As structural evaluation indices, maximum hover efficiency is expected, so the main research highlights are summarized as followed: 1) to design the propulsion group for maximum thrust/power ratio with better hover efficiency and lower mass; 2) the low Re aerodynamic environment is also considered to show the stronger rotor interferences and vortex movement in the outflow; 3) the adjacent rotor spacing ratio is introduced to promote a propulsion system with the greatest degree of capacity; 4) it has a much wider class than previous studies including both 3D numerical simulations and experiments, and 5) it goes further by introducing the coaxial rotors as the engineering design which is feasible to satisfy the design constraints whilst optimizing the combined electric and aerodynamic efficiency for typical hover conditions.

Considering that the aerodynamic effect between rotors is related to the arrangement of rotors, it is necessary to figure out the influence of the rotor arrangement on the aerodynamic performance. At the same time, the optimal rotor arrangement for this kind of Hex-rotor MAV with coaxial rotors is still unknown and insufficient in aerodynamic analysis related to the hover efficiency. In view of these facts, our current works seeks to answer the following questions:

How does a change in rotor spacing between coaxial rotors affect the propulsive efficiency as a whole?

Where the higher thrust comes from considering the combination of three coaxial rotor pairs?

How do the interferences change into the benefit for the thrust increment without power increment for some cases?

What implications do these results have for the design process?

II. THEOREITICAL ANALYSIS

A. ROTOR SPACING

The rotor arrangement of the Hex-rotor MAV is shown in Figure 1.

In Figure 1, $D$ is the diameter of the rotor, $T$ is the rotor thrust, and $\Omega$ is rotational speed of the rotor. $s$ is the distance between the upper rotor and the lower rotor of coaxial rotors. According to our previous studies related to the theoretical and experimental research, the coaxial rotors with $s = 0.19D$ has the best aerodynamic performance [16] which is also applied in this paper. In addition, $L$ is the distance between the centers of adjacent coaxial rotors, and $L$ is equally distributed as $1D$, $1.2D$, $1.4D$, $1.6D$, $1.8D$, $2D$ to avoid any rotor collision or oversize of the vehicle.

B. FLOW FIELD OF THE HEX-ROTOR MAV

Figure 2 shows the distribution of wake vortices and flows of the Hex-rotor MAV.

In Figure 2, it is noted that the interaction of the Hex-rotor MAV mainly include two parts: 1) interference between adjacent coaxial rotors. The distortion of the wake vortices of the adjacent coaxial rotors will affect the aerodynamic performance of the Hex-rotor system by causing extra power consumption. Especially, when the rotor spacing $L$ is too small, the interference of wake vortices will be intensified and leading vibration. On the contrary, with the spacing $L$ increases large enough, the overlapping region of wake vortices is decreased with the decreased interference gradually. However, an excessive large spacing will also increase vehicle mass or power consumption by a long rotor arm, and eventually put extra difficulties to manipulate. 2) the downwash and wake vortices between the upper and lower rotors of the coaxial rotor. This kind of wake vortex involved with coaxial rotor is totally different from any MAV with planar rotors and is also accounted to the complexity of the rotor interference.

Due to the compact structure, strong anti-interference ability and outstanding yaw capacity of this kind of rotor arrangement, the rotor interference is needed to be treated carefully.
C. AERODYNAMIC PARAMETERS
For the aerodynamic environment for the Hex-rotor MAV, the Reynolds number is defined as follows:

\[ \text{Re} = \frac{\rho v c}{\mu} \]  

(1)

where \( \rho \) is the air density, \( \text{kg} / \text{m}^3 \); \( v \) is the velocity; \( c \) is the chord length; \( \mu \) is dynamic viscosity coefficient of air.

In order to effectively evaluate the aerodynamic performance of the Hex-rotor MAV, two indexes are adopted for evaluation: power loading and hover efficiency.

1) POWER LOADING
The power loading (PL) is defined as [18]:

\[ PL = \frac{C_T}{\Omega R C_P} = \frac{T}{Q \Omega} \]  

(2)

where \( T \) is thrust of the rotor, N; \( P \) is power of the rotor, W; \( A \) is rotor disk area, \( \text{m}^2 \); \( \Omega \) is rotational speed of the rotor, rad / s; \( R \) is radius of the rotor, m; \( Q \) is torque, Nm; \( \rho \) is the fluid density, \( \text{kg} / \text{m}^3 \); \( C_T \) is the thrust coefficient of the rotor; \( C_P \) is the power coefficient of the rotor.

The thrust coefficient and power coefficient of the rotor are calculated according to the following formula [17].

\[ C_T = \frac{T}{\rho A \Omega^2 R^2} \]  

(3)

\[ C_P = \frac{P}{\rho A \Omega^2 R^3} = \frac{Q \Omega}{\rho A \Omega^2 R^3} = \frac{Q}{\rho A \Omega^2 R^3} \]  

(4)

In general, the max \( PL \) is characterized by maximizing energy efficiency which means that the MAV has the best payload capability. Additionally, \( PL \) comparisons are not affected by working conditions or their own configurations. Thus, it can directly show the required energy with a given thrust for the rotor system.

2) HOVER EFFICIENCY
The hover efficiency is related to the load capacity and hover time of the multi-rotor MAV. Generally, a large load capacity is accompany a better anti-interference ability, which is characterized by the figure of merit (FM).

\[ FM = \frac{C_T^{3/2}}{\kappa \frac{C_L^{3/2}}{\kappa} + \frac{\sigma C_{d0}}{8}} \]  

(5)

where \( \kappa \) is the induced power factor, \( C_{d0} \) is the drag coefficient, and \( \sigma \) is the rotor solidity. In this paper, the rotor solidity is 0.128, the induced power factor is 1.42, and the drag coefficient is 0.1.

The spacing ratio \( i \) is introduced as the dimensionless quantification to discuss the variation of the rotor spacing \( L \) which is defined as

\[ i = \frac{D}{L} \]  

(6)

Therefore, the spacing ratio \( i \) is 0.5, 0.56, 0.63, 0.71, 0.83, 1, respectively.

III. EXPERIMENTS
A. EXPERIMENTAL SETUP
In the test, the thrust is measured by the thrust sensor, and the power is obtained by the measured current and voltage. The measured values of the sensor, tachometer are transmitted to the computer through data card. The thrust, speed and power of the Hex-rotor MAV with different spacing are calculated and converted into the parameters such as power loading, thrust coefficient, power coefficient and hover efficiency automatically. These parameters are characterized as the aerodynamic performance of rotor system.

The sketch of the experimental setup is shown in Figure 3.

![Figure 3. Experimental setup.](image)

As showed in the Figure 3, the rotor has two blades with a diameter of 400 mm and a weight of about 0.015 kg. The \( Re \) of the rotor tip is ranged from \( 0.79 \times 10^5 \) to \( 1.21 \times 10^5 \). The flying attitude of the MAV is controlled by an electronic speed controller. The experimental instruments of test platform mainly including: (1) power system: DC power supply (model: ACE-GESHI lithium polymer battery), brushless DC motor (model: EM2835) and PWM speed control system. (2) The measurement parameters mainly include the rotational speed, thrust and power of the rotor. The rotational speed is obtained by the tachometer (model: TM-5010K, accuracy: \( \pm 0.01\% \pm 1d \)). The thrust is obtained from the micro thrust sensor (model: PLD204D-19, accuracy: 0.5% F.S). The power is calculated by the recorded current and voltage values [19]–[21]. According to the calculation of Kline-McClintock equation, the uncertainties of \( C_T \), \( C_P \) and \( PL \) are 1.2%, 1.1% and 1.5%, respectively.

B. EXPERIMENTAL RESULTS
To present the experimental results with a more intuitively way, the data of \( i = 1 \) is assumed as the baseline as the comparison. Figure 4 shows the thrust variation compared with \( i = 1 \).

In Figure 4, it shows that the thrust of \( i = 1(L = D) \) obtained the minimum thrust in general which may caused by the strong interference between adjacent coaxial rotors. As the spacing increasing, the interference of adjacent coaxial rotors is diffused where the rotor interference between the upper rotor and lower rotor began to domain the flowfield, especially for a relatively large spacing L. Especially, thrust at \( i = 0.56 \) and 0.63 shared a max variation up to 8%. It is may be the optimal state where the two kind of interference
are offset to some extent. However, it is also interesting to note the thrust of \( i = 0.56 \) at \( Re = 0.89 \times 10^5 \) decreased dramatically, which is caused by the vibration of the Hex-rotor system. Additionally, the thrust of \( i = 0.63 \) is 6.09% greater than that of the other spacing when \( Re \) is more than \( 1.05 \times 10^5 \).

Figure 5 shows the variation of power loading compared with \( i = 1 \).

In Figure 5, it is noted that the variation of power loading shared a small change. Also, it is obvious that the \( PL \) of \( i = 0.50 \) and 0.56 at \( Re = 0.89 \times 10^5 \) decreased to minimum which is consistent with the thrust variation. According to the Equation (2), the \( PL \) will decrease with a decreased thrust and increased power which may be consumed by the vibration of the Hex-rotor system. In addition, the power loading of \( i = 0.63 \) is up to 13% at \( Re = 1.16 \times 10^5 \).

Figure 6 shows the variation of hover efficiency compared with \( i = 1 \).

In Figure 6, it is noticed that the hover efficiency of \( i = 0.63 \) kept at a greater value, and it reached the maximum at \( Re = 1.16 \times 10^5 \) which is 9.17% higher than that of \( i = 1 \). Also, the hover efficiency of \( i = 0.71 \) and \( i = 0.83 \) shared a similar value with \( i = 1 \) without any improvement. It can be concluded that too small spacing is not conducive to improve hover efficiency of the Hex-rotor MAV.

Therefore, the proper interference between the rotors is conducive to improve the aerodynamic performance of the Hex-rotor MAV with the optimal spacing of rotors with more thrust. Eventually, a better aerodynamic performance of the Hex-rotor MAV is obtained at \( i = 0.63 \).

IV. NUMERICAL SIMULATIONS

A. SIMULATIONS SETUP

The average Navier-Stokes equation is adopted as the governing equation for numerical simulation, and the Spalart-Allmaras (S-A) turbulence model is selected in simulation. Additionally, the SIMPLE algorithm is applied for the pressure and velocity coupling, and the PISO algorithm is adopted for all transient flow calculations. Also, PRESTO discretization is used in this paper without interpolation errors. Furthermore, central differencing scheme is chose for S-A with second-order upwind scheme. The sliding mesh is applied to solve for the motion of the rotors due to the highly unsteady nature of flow involved in the study and the time-step size is 10e-5. The meshing distribution of the entire computing domain are shown in Figure 7.
to handle the low Reynolds number flows or multiple viscous boundary layers. Also, the mesh on the rotor tip is refined to reach the independence state, and the max element metrics is below 0.8 to capture the flow detail of the rotor tip and the interfaces between stationary and rotating regions.

A comparison between the experiment and CFD results are showed in the Figure 8 to validate the accuracy of the CFD. As showed in the Figure 9, both the thrust coefficient $C_T$ and power coefficient $C_P$ are generally in good agreement and the CFD results are slightly higher than the experiment. This difference may be resulted by the introduced external disturbance in experiments and the simplified model of propeller applied in simulations.

B. SIMULATIONS RESULTS

Figure 9 shows the outflow distribution between adjacent coaxial rotors.

In Figure 9, it shows that as the spacing increases, the interference between adjacent coaxial rotors decreases gradually, and the overlapping area of their outflow reduces gradually. As the spacing increases further, the interference between adjacent coaxial rotors eventually disappears, and the outflow no longer interferes with each other. In the meanwhile, it can be found that the outflow distribution area of $i = 0.56$ is relatively small, which shows that the interference between the rotors is beneficial to improve the overall aerodynamic performance to a certain extent.

Figure 10 shows the velocity contour of coaxial rotors.

As showed in Figure 7, the computational domain is divided into a cylinder stationary region and six rotating regions, which has a total size of about 4.3 million cells. The grid independency study showed that the mesh is sufficient
In Figure 10, it can be noticed that as the spacing increases, the downwash velocity field starts to concentrate from the divergent state to the rotor central axis. At the same time, it is found that the area of the downwash velocity contour of \( i = 0.63 \) kept at the largest. The arrangement of the downwash velocity gradient boundaries is diffused at \( i = 0.63 \) and \( i = 0.56 \), which suggests that the downwash velocity changes slowly, and the overall aerodynamic performance is relatively stable. It also confirmed that the variation of power loading in Figure 5, where the PL is the maximum for \( i = 0.63 \) and \( i = 0.56 \) at \( Re = 1.16 \times 10^5 \) may come from the evenly distributed downwash.

Figure 11 shows the velocity vector distribution of the Hex-rotor MAV.

In Figure 11, it shows that as the spacing increases, the velocity vector distribution of the Hex-rotor MAV becomes more and more uniform and full, and the uniformity of the velocity vector distribution first increases gradually and then decreases. In addition, the velocity vector distribution is relatively uniform at \( i = 0.63 \), and the overall flow field is stable in this case. It also confirmed that the higher hover efficiency presented in Figure 6 is related to the uniformity of the velocity distribution.

![FIGURE 11. Velocity vector distribution of Hex-rotor MAV in hover (\( Re = 1.16 \times 10^5 \)). (a) \( i = 0.83 \). (b) \( i = 0.71 \). (c) \( i = 0.63 \). (d) \( i = 0.56 \). (e) \( i = 0.5 \).](image)

In Figure 12, it is noticed that the vortices generated by each coaxial rotors will overlap with each other at smaller rotor spacing which may affect the shape of the overall vortex. With the increase of spacing, the interference between adjacent coaxial rotors is weakened, and the vortices are separated from each other to further ensure the integrity of the vortex. However, the overall aerodynamic performance may be weakened when the interference from upper rotor and lower rotor of coaxial rotors domain the flow field even the interference of adjacent coaxial rotors is wake for larger rotor spacing. In addition, it is found that the vortex shape of the Hex-rotor appears to be integrated at \( i = 0.63 \) which is consistent with the PL presented in Figure 5.

Figure 12 shows the overall vortex distribution of Hex-rotor MAV.

![FIGURE 12. Vortex distribution of Hex-rotor MAV in hover (\( Re = 1.16 \times 10^5 \)). (a) \( i = 0.83 \). (b) \( i = 0.71 \). (c) \( i = 0.63 \). (d) \( i = 0.56 \). (e) \( i = 0.5 \).](image)

Figure 13 shows the pressure contour of the rotor tip of coaxial rotors.

The pressure difference between the upper and lower surfaces of the rotor is characterized with the thrust variation. Figure 13 shows that the pressure difference is presented with
larger negative pressure and less positive pressure at \( i = 0.63 \) which means that a higher thrust is generated in this case. It also shows that the pressure difference at \( i = 0.56 \) and \( i = 0.83 \) are basically small which is consistent with the thrust variation showed in Figure 4.

V. CONCLUSION

In this paper, the power loading and hover efficiency of the Hex-rotor MAV are analyzed theoretically, and the numerical simulation and experimental study are presented in detail. According to the comparison of the numerical simulation results such as the velocity distribution, pressure and velocity contour, and experimental results like thrust and power variation, conclusions are as follows:

(1) For smaller rotor spacing, the wake vortices of adjacent rotors interfere with each other, which will lead to the extra power consumption. In addition, the shape and size of the vortex and the velocity distribution of the downwash may be the potential factors to affect the whole aerodynamic environment. Also, for larger rotor spacing, the extra weight may increase the difficulty in flight control without flexibility.

(2) The hover efficiency is improved when the area of downwash velocity field is greater, or there is no divergent in the downwash flow, or the vortex remains relatively complete, especially at \( Re = 1.16 \times 10^5 \). Combined with pressure distribution and velocity distribution of the flow field, the \( PL \) and \( FM \) values are relatively higher at \( i = 0.63 \) where the aerodynamic performance is much improved with larger thrust and lower power. Thus, it can be applied as the best rotor arrangement of the Hex-rotor MAV.

(3) For a proper spacing ratio, the rotor interference may be beneficial to improve the payload capability and the overall aerodynamic performance without increasing the extra power. Further work will be involved with wind effect on the whole fuselage of the Hex-rotor MAV.

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