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The aerodynamic performance of Non-planar hex-rotors aircraft subjected the horizontal wind disturbance

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Abstract: The non-planar hex-rotor aircraft mentioned in this article can change its flight status by simply changing the tilt angle of the rotor. In this paper, mainly studied the best aerodynamic performance of a non-planar hex-rotor aircraft under the influence of horizontal wind (0m/s, 2.5m/s and 4m/s). Firstly, the rotation speed of the rotor is a fixed value (2200r/min) in the low-speed wind tunnel test, the horizontal wind speed and the tilt angle of the rotor are variable values, the thrust, power consumption and power loading(PL) values of the aircraft are obtained. Secondly, the computational fluid dynamics(CFD) method is used to simulate the aerodynamic performance of a non-planar hex-rotors aircraft when subjected to a horizontal wind to obtain the simulation results. Finally, comparing the experimental values and the simulation values, it is found that the horizontal speed has a greater impact on the thrust and power consumption of the non-planar hex-rotor aircraft. From the change of PL values, it is concluded that the horizontal wind speed is 0m/s, 2.5m/s, 4m/s, the best inclination angle is 10°, 30°and 50°, and the strongest anti-wind performance.

Keywords: non-planar hex-rotor aircraft, horizontal wind, aerodynamic performance, CFD, wind tunnel test

Introduction

The multi-rotors aircraft are widely used in the field of civilian and military[1,2], because of it have the small size, simple structure and high flexibility. In particular, the non-plane hex-rotors aircraft can change its attitude by changing the tilt angle of rotor, which is different from the plane aircraft[3,4](its flight attitude changed by changing the fuselage angle). The non-plane hex-rotors aircraft has largely total thrust, more degrees of freedom and high flight stability. However, due to changing the tilt angle can make the pneumatic layout more complicated, especially in the case of natural flow, the aerodynamic influence between rotors is more obvious.

However, most of the recent research on aerodynamic characteristics and control of planar hex-rotors aircraft. Tinney et al.[5] demonstrated the pressure of noise on the rotor is related to the number and size of the rotor, and the aerodynamic performance of hex-rotors aircraft affected by near-field acoustics. Parra et al.[6] proposed a method of aerodynamic analysis to reduce the over-pressure and use the generated turbulence for hex-rotors aircraft. Based on the simulation method of fluid-structure coupling, Wu et al. analyzed the flow field force acting on the rotor[7]. Research on hex-rotors aircraft control, Le et al[8]. considered that the singularity in the space coordinates would cause the failure of the aerodynamic model and the control system, and proposed a simulation based on cascaded PID control. A comprehensive control system for autonomous hex-rotors aircraft based on visual-servoing and cascaded proportional derivative (PD) controller is proposed by Ahmed et al.[9]. Al-Mahasneh et al.[10] analyzed an adaptive neural network (NN) controller for a hex-rotors aircraft with uncertain dynamics.

Moreover, there are relatively few studies on the aerodynamic characteristics of non-planar multi-rotors aircraft. Chen et al.[11] studied the aerodynamic interference problem of a non-planar quad-rotors aircraft hovering near the ground, and found that when the hover height is less than the diameter of the aircraft, the ground effect is obvious. When the maximum load of the fuselage is 12% of the vertical thrust, an obvious fountain flow appears. Lei et al. studied the aerodynamic performance of a non-planar quad-rotors aircraft, since the outflow of non-planar quad-rotors aircraft is stronger, the thrust of the rotor increases with the increase of the tilt angle, and it also increases the power loss[12]. Du Siliang et al.[13] analyzed the aerodynamic interference of the tilting quad-rotors aircraft and concluded that the front rotor is the dominant factor affecting the aerodynamic interference of the entire aircraft.

For the research of aircraft in the gusty environment. LIU Zhi-qiang et al.[14] was studied the effect of horizontal gusts on double-rotors aircraft and believed the horizontal wind affects the airflow structure of the rotor surface, causing the thrust characteristics to change. Sudhakar et al[15]. research the effect of vertical gusts on the aerodynamic performance of the aircraft, and pointed out that vertical gusts would destroy the symmetry of the airflow. In short, the aerodynamic performance of the non-planar hex-rotors aircraft subjected to horizontal wind disturbance has not been studied yet, so it is meaningful to analyze the aerodynamic performance of the non-planar hex-rotors aircraft in the circumstances of horizontal wind.

Analysis of Theoretical Model

The base frame of non-planar hex-rotors aircraft is shown in the Fig.1, it can been see that the six rotors are arranged in an equilateral hexagon. The angle between two adjacent rotors is 60° and the direction of rotating are inverse. Different from the usual aircraft, the motor of non-planar aircraft rotate around the arm at a certain angle, and the adjacent motors rotated at the same angle but in opposite directions.

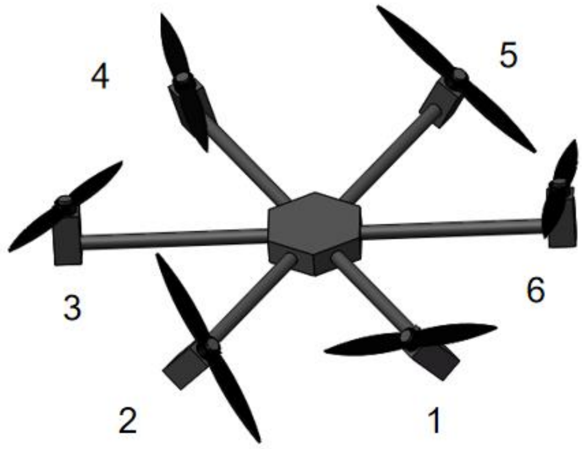
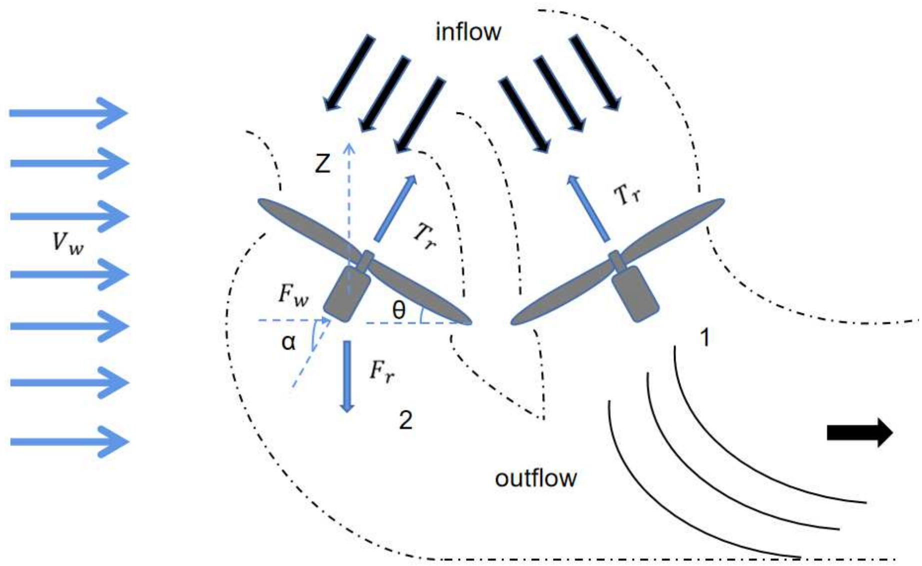


Fig.1 The non-planar hex-rotors aircraft

The aerodynamic influence of non-planar hex-rotor aircraft are more complex, because of the every rotor has a tilt angle, it makes the aircraft generate three face to face unit and back to back unit respectively , as shown in the Fig.2.

(a)



(b)

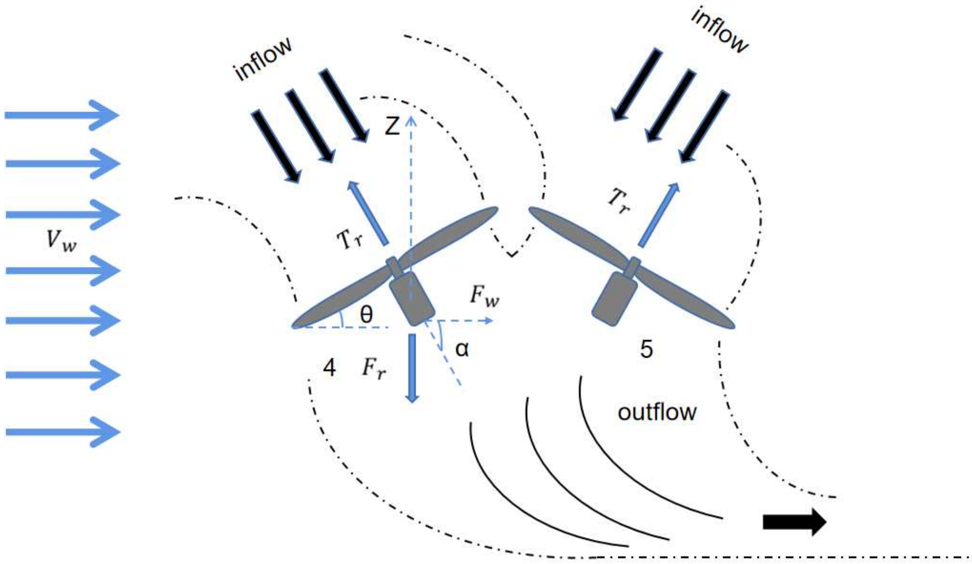


Fig 2.The aerodynamic interference of adjacent rotors with horizontal wind. (a) face to face unit. (b) back to back unit.

This will increase the disturbance to the inflow and outflow. For non-planar aircraft, a rotor thrust has an angle θ with the Z axis, and a horizontal wind force has an angle α with the vertical line of the rotor surface. The two angle are complementary as follow:

$$\alpha = 90^\circ - \theta \qquad (1)$$

In face to face unit, the thrust of rotor i is

$$T_{zi} = (T_{ri} + F_w / \cos\alpha)\cos\theta - F_r, \quad (2)$$

where i=2, 5, 6, F_w is the horizontal force of incoming flow on a rotor and the force on each rotor is related to the surrounding flow field, F_r is total weight of the rotor and motor.

In back to back unit, the thrust of rotor n is

$$T_{zn} = (T_{rn} - F_w / \cos\alpha)\cos\theta - F_r, \quad (3)$$

where n=1, 3, 4.

Given the individual thrust of the six rotors, the total thrust T of the vehicle is equal to

$$\mathrm{T} = \sum_{j=1}^{k} \mathrm{T_j} \qquad , \qquad k = 6. \qquad (4)$$

Since the aerodynamic influence between rotors of non-planar aircraft is more severe, this paper gives two main influencing factors, thrust coefficient C_T and power coefficient C_P[16].

$$C_T = \frac{T}{\rho A \omega^2 R^2} \quad (5)$$

$$C_P = \frac{P}{\rho A \omega^3 R^3} \quad (6)$$

Where ρ (kg/m^3) is air density, A (m^2) is area of the rotor, ω $(r/\min)$ is speed of the rotor and R (mm) is radius of the rotor.

To analyze the aerodynamic performance of the aircraft under the condition of wind disturbance, the power loading(PL)[17] is introduced in this article, which is defined as follows:

$$PL = \frac{C_T}{\omega R C_P} \quad (7)$$

Substituting (5) and (6) into (7), finally get:

$$PL = \frac{T}{P} \quad (8)$$

Wind tunnel test

Experimental setup. When the non-planar hex-rotors aircraft works under the condition of horizontal wind, a large part of the thrust is generated at the tip of the propeller, so the propeller will bend in the positive direction of thrust. The flexibility of the rotors plays a decisive role in the aerodynamic performance, so the flexible rotor is adopted[18]. Be different from the planar aircraft, the non-planar hex-rotor aircraft needs to change the rotors of tilt angle to achieve the flying condition, choosing the rotary motor to actuated. In the test, the every aircraft parameter is shown in the Table 1, L is the spacing between adjacent rotors and D is the rotor diameter.

Rotor Diameter(mm)	Motor Speed(rpm)	L/D	Wind Speed(m/s)
400	2200	1.2	0, 2.5, 4

Table.1 The every aircraft parameter

To study the aerodynamic characteristics of non-planar hex-rotor aircraft in horizontal wind, a test platform of low speed wind tunnel can shown as Fig.3. The test platform are consist of the contraction section, test section, expansion section, safety net, and power section. To ensure the stability of the test wind, the plate of active grid[19] was installed in front of the contraction section and the air inlet of the test section is a square of 2.6m x 2.6m. There are tachometer, force sensor and power supply connected in the test section to collect the value of rotor speed, trust and power respectively. Considering that the wind speed encountered by the micro air vehicle in the normal working environment is generally lower than 6m/s, the wind tunnel test adopts the uniform wind of 0m/s, 2m/s and 4m/s to analyze it and the change of wind speed is controlled by the motor drive of the power section. The changing voltage and current signals are collected by the thrust sensors on each rotor and transmitted to the data analysis system. The variable of voltage and current is converted into the corresponding thrust and power and displayed on the terminal. In the test, the parameter of thrust sensor is shown in the Table 2.

Model	precision	Rated output
SBT674	0.1%	1.5±10%

Table.2 The parameter of thrust sensor

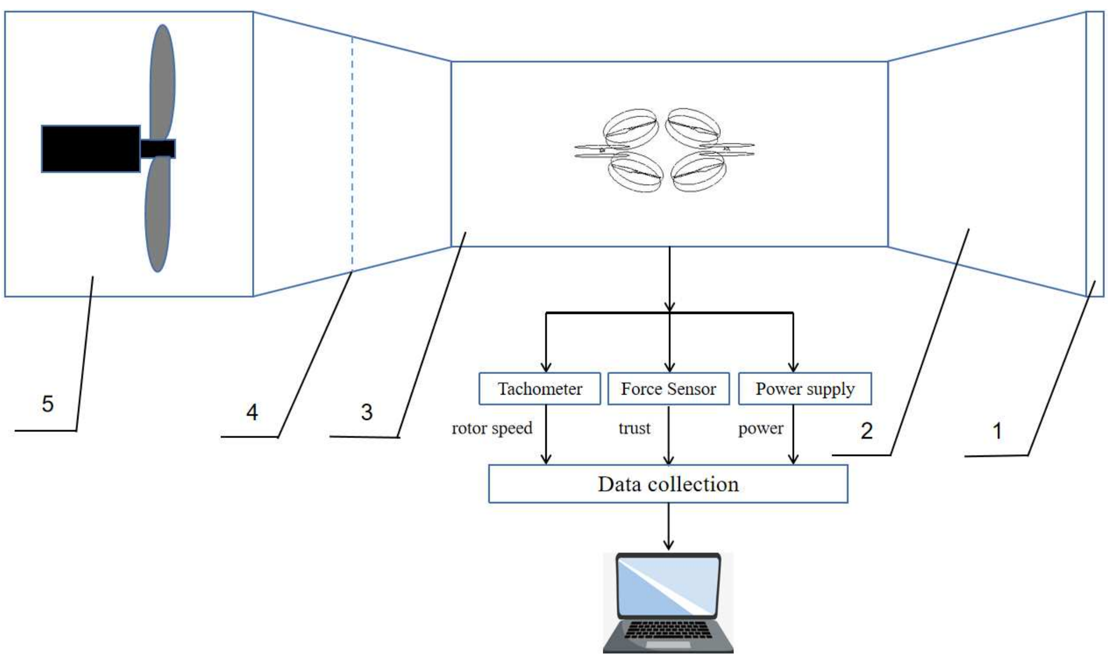


Fig.3 Test platform. (1)the plate of active grid. (2)contraction section. (3)test section. (4)expansion section and safety net. (5)power section.

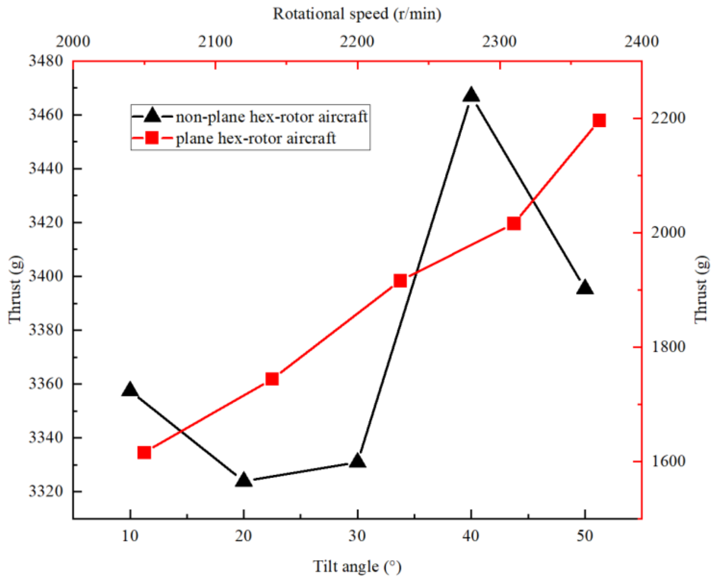
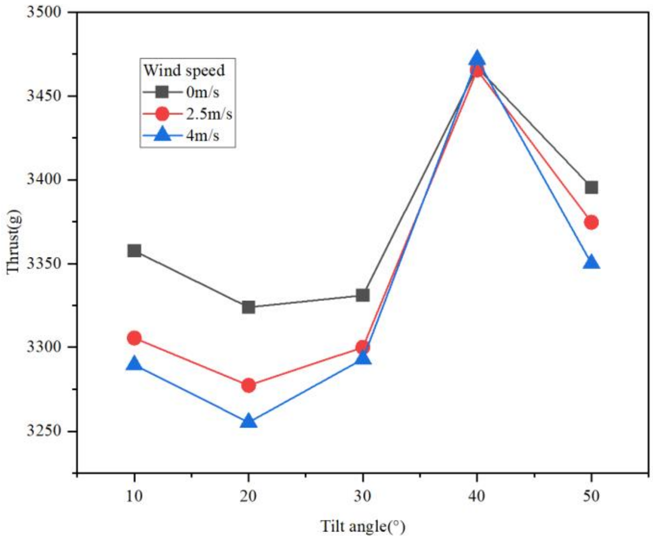


Fig 4 Comparison of thrust between planar and non-planar hex-rotors aircraft

Experimental result. For the non-planar hex-rotor aircraft system, rotor tilt angle and horizontal wind speed are increased from 10°to 50°and 0m/s to 4m/s in the this test. Fig.4 shows the comparison of the thrust value of non-planar and planar hex-rotor aircraft, it can be clearly obtained that the planar hex-rotor aircraft as the increase of rotor speed, overall thrusts are also gradually increasing. But for a non-planar hex-rotor aircraft, no matter what the tilt angle is, the thrust is greater than that of a planar hex-rotor aircraft and produces at least 75% more total thrust than the planar hex-rotor aircraft in the motor speed of 2200r/min. It because of the inclination of each rotor of the non-planar aircraft, which makes the aerodynamic influence more stronger between rotors, thereby increasing the thrust.

The figure below shows the effect of the tilt angle on the thrust and power consumption of the non-plane hex-rotor aircraft under the horizontal flow state in the wind tunnel test.

(a)



(b)

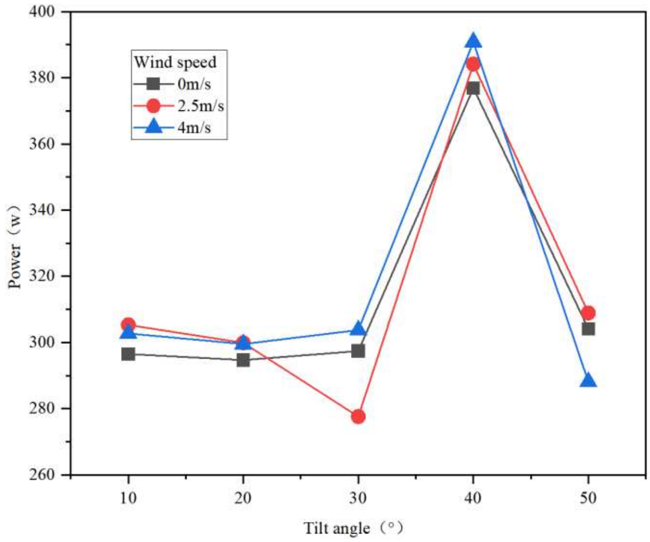


Fig.5 (a)The influence of different horizontal wind speeds on the thrust of non-planar hex-rotors. (b) The influence of different horizontal wind speeds on power consumption of non-planar hex-rotor.

As shown in Fig.5, it can clearly see that the relationship between thrust and power is generally positive. Obviously, as the wind speed increases, the impact on thrust also increases, showing a downward trend. However, the aspect of power consumption show a complex relationship. The power consumption of the aircraft under the interference of horizontal wind is greater than that under no wind, this phenomenon possibly due to wind increase the aerodynamic interference among the rotors. The thrust changes are consistent and the peak at 40°in different wind speed shown in Fig.5a. Shown in Fig.5b, the wind speed have a same trend at 0m/s and 4m/s, but the power drops sharply to the lowest point at wind speed of 2.5m/s and tilt angle of 30°, it might be reached a optimal aerodynamic performance and makes the maximum thrust and the lowest power consumption.

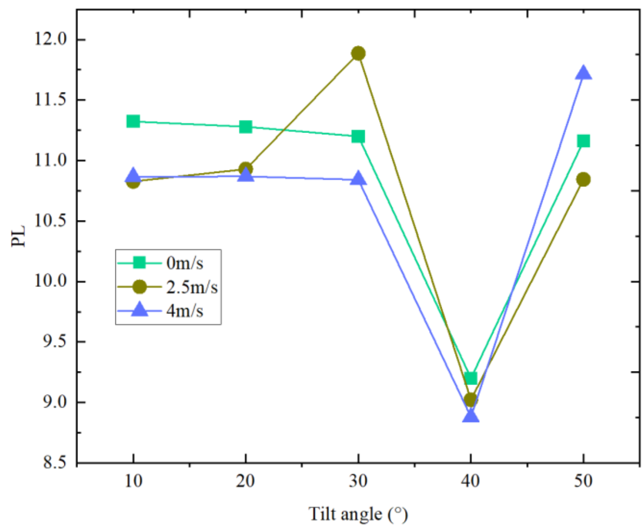


Fig. 6 The amount of change in power loading

It can be seen from Fig.5 that the greater the thrust of aircraft, the greater the power loss. For evaluating the aerodynamic performance of an aircraft, the power loading(PL) is most important. Tilt angle from 10° to 50°, the trend of PL are shown in Fig.6. The aerodynamic performance shown is not the same under different wind speed, corresponding peaks appears in 10°, 30° and 50° respectively.

Numerical simulation

For evidencing the accuracy of the experiment and analyzing aerodynamic characteristics, this paper uses the computational fluid dynamics(CFD) method to numerically simulate the non-planar hex-rotor subjected to horizontal flow. Considering that the aircraft can withstand light breeze(1.6-3.3m/s) and gentle breeze(3.4-5.4m/s) within the controllable range[20], selecting the wind speed of 0m/s, 2.5m/s and 4m/s in this method. Combining the reasonableness of the tilt angle of the non-planar aircraft, choose 10°to 50°as the tilt angle variable.

Simulation setup. ANSYS FLUENT is selected to simulate the flow field of non-planar hex-rotor aircraft in the different case of horizontal wind speed. Fig.7 shows the mesh distribution of entire flow field and the rotating field of face to face unit and back to back unit with 10.05 million cells. Choosing the Polyhedral mesh to improve the computational efficiency. Additionally, the viscous model setup to Spalart- Allmaras(S-A) and the pressure correction set to Semi Implicit Method for Pressure Linked Equations (SIMPLE) algorithm, the Pressure, Momentum and Modified Turbulent Viscosity are all setup to second-order upwind for spatial discretization.

Finally, the under-relaxation factor is used to 0.3 to obtain the greater computational convergence and rotor speed at 2200r/min.

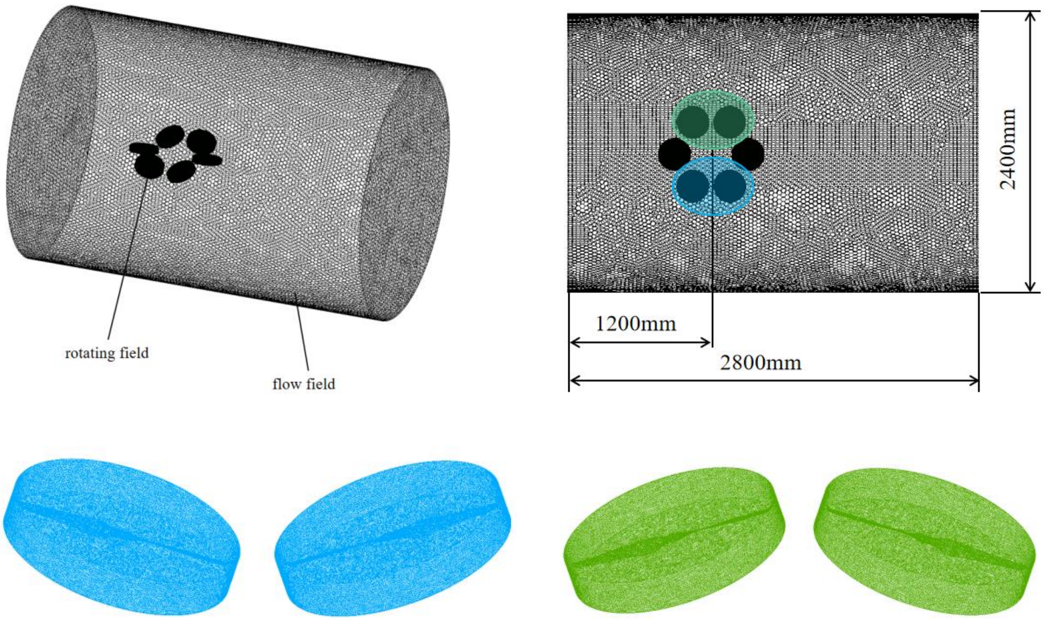
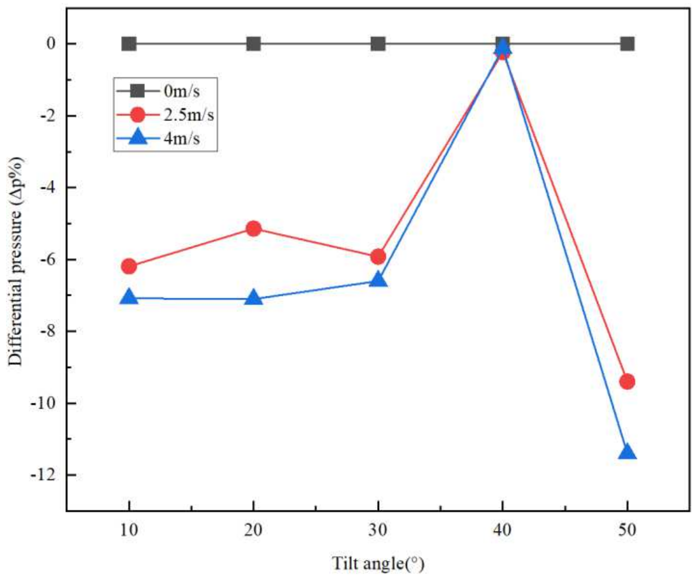


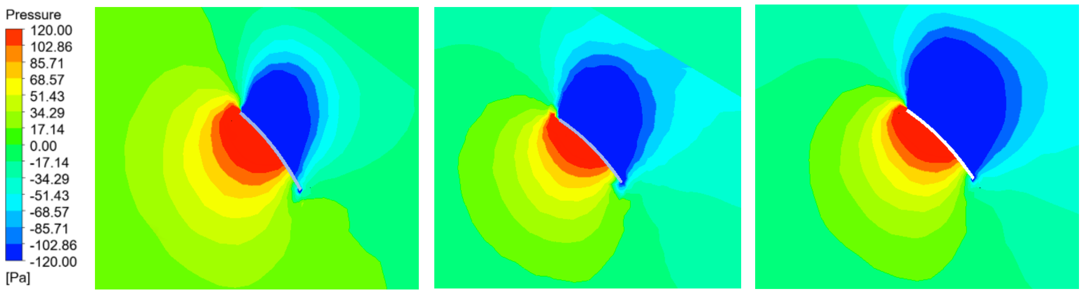
Fig.7 Mesh distribution

Simulation result. In order to receive the variation of thrust in simulation, extracting the differential pressure near the blade-tip as a result. Fig.8(a) shows the comparison variation of differential pressure of upper and lower surface as function of different rotor tilting angle and different horizontal wind speed in 0.8R of rotor. It can be seen that the differential pressure decrease with the wind speed increase, when the tilt angle reaching 40°and 50°, wind speed have minimal and greatest impact on pressure difference respectively. Fig.8(b) shows the variation of blade-tip pressure at different wind speed and an inclination angle of 50°. Obviously, wind speed greatly weakens the positive pressure area on the lower surface of the rotor and slightly strengthens the negative pressure area on the upper surface of the rotor.

(a)

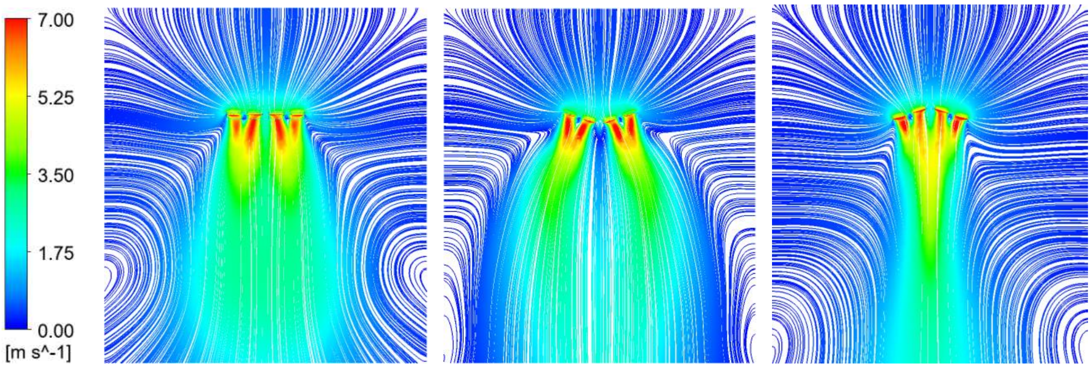


(b)



50° - 0m/s 50° - 2.5m/s 50° - 4m/s

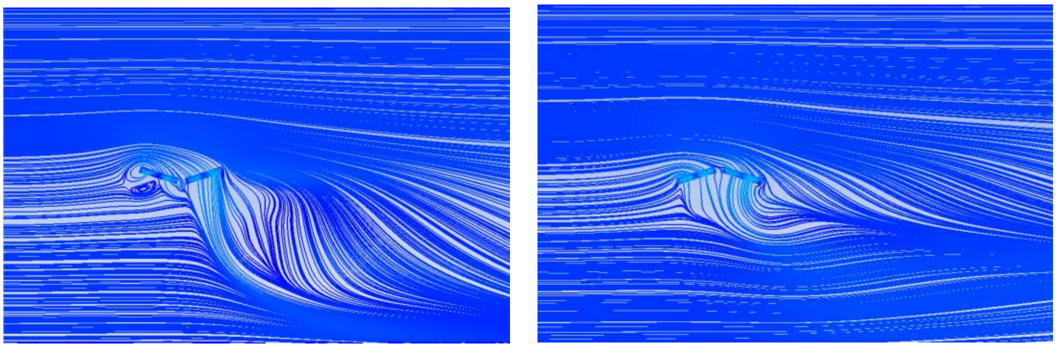
Fig. 8 Distribution of pressure difference(ΔP) between the upper and lower surfaces of the tip of rotor. (a) Comparison of pressure difference at different wind speeds. (b) Pressure cloud diagram of the rotor tip at the tilting angle of 50°.



(a) (b) (c)

Fig.9 Streamlines of different rotor units. (a) planar rotor unit. (b) face to face rotor unit. (c) back to back rotor unit.

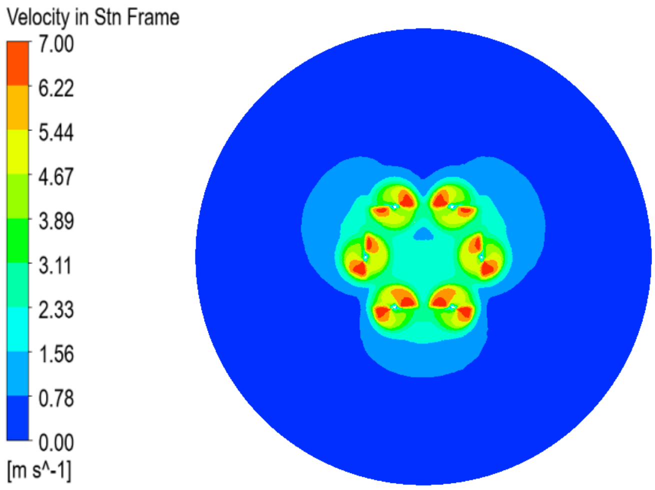
There are three types of model combinations between adjacent rotors of the hex-rotors aircraft, which are planar unit, face-to-face unit and back-to-back unit. The streamline distribution in no horizontal wind is shown in Fig.9. Each model combination corresponds to a different streamline distribution. Compared with planar units, the inflow streamlines of face-to-face units and the outflow streamlines of back-to-back units are more denser, the speed of outflow are obviously increase. This is because the thrust of non-planar aircraft is larger than that of planar aircraft.



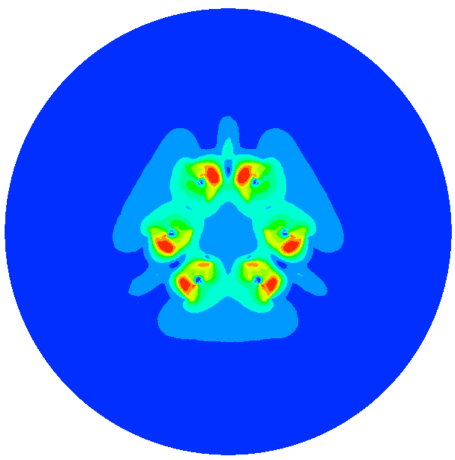
(a) (b)

Fig.10 Streamline distribution. (a) face to face unit. (b) back to back unit.

Fig.10 shows the streamline distribution of face to face and back to back unit affected by the horizontal wind. Due to the influence of horizontal wind, the distribution of streamlines is also irregular, and the streamlines of inflow and outflow are relatively sparse. Additionally, the vortex phenomenon appears at the tip the blade and under the blade and severely damaged the outflow of the left rotor in face-to-face unit as shown Fig.10(a). It is the main reason why the thrust of non-planar aircraft decreases when subjected to horizontal wind.



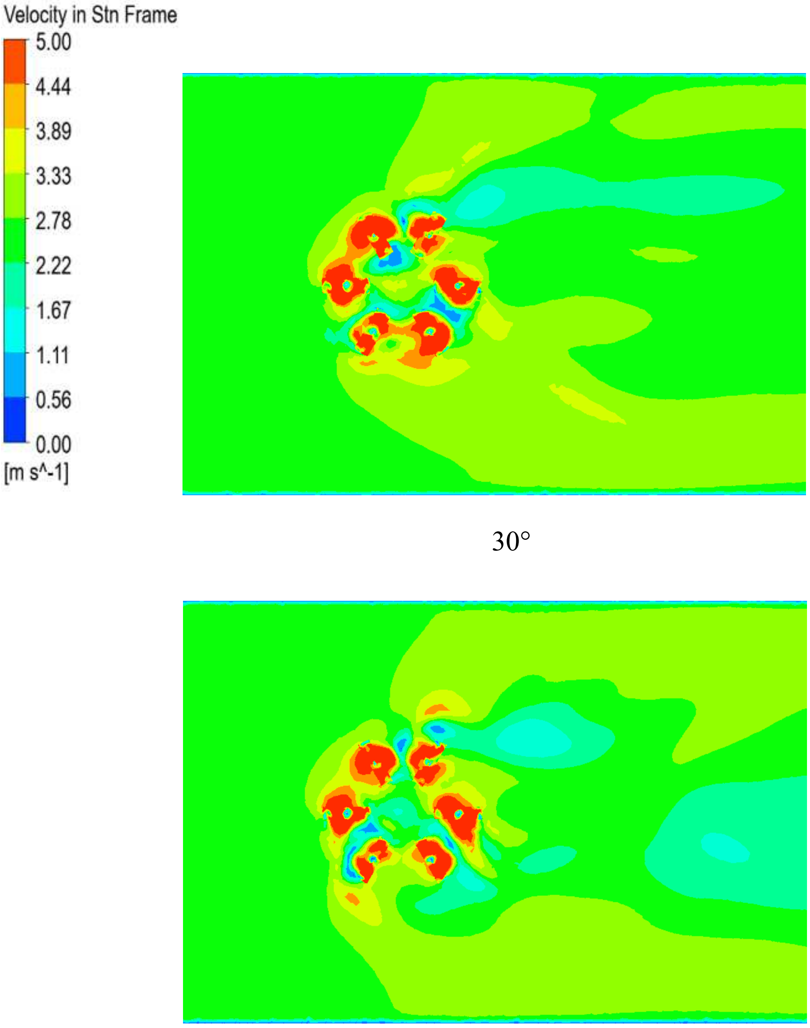
10°



40°

Fig.11 Velocity cloud diagram at the speed of 0m/s.

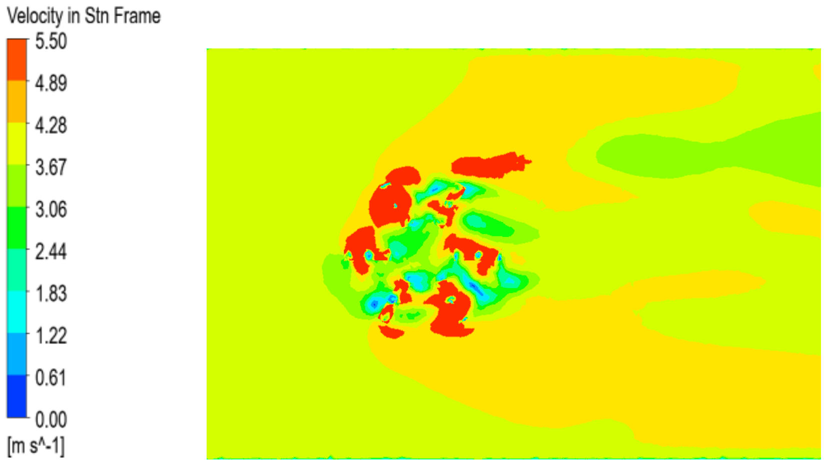
The non-planar hex-rotors are subjected to horizontal wind, the airflow distribution and speed changes between the rotors are more obvious, as shown in the Fig.11-13. When the horizontal wind speed is 0m/s, the distribution of the velocity cloud is symmetrical are shown in Fig.11. Comparing the tilt angle of 10°and 40°, the airflow distribution between the rotors has changed and the aerodynamic interference increases at 40°. This phenomenon will lead to an increase in power loss, thereby reducing the power loading(PL).



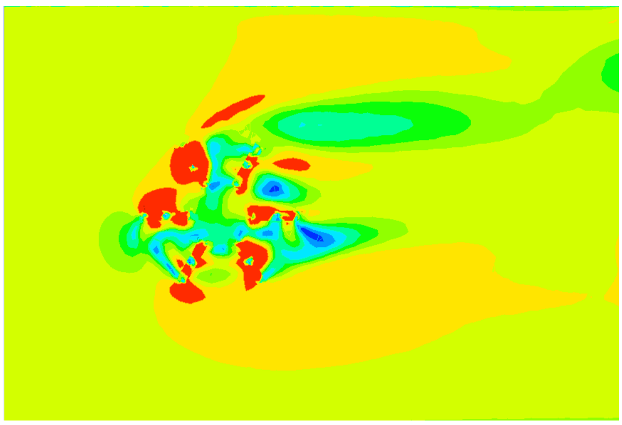
40°

Fig.12 Velocity cloud diagram at the speed of 2.5m/s.

With the wind speed increases, the speed cloud image appear an irregular arrangement and no longer has symmetry, as shown in the Fig.12-13. When the horizontal wind speed is 2.5m/s as shown in Fig.12, the tilt angle reaching 40°, the velocity distribution on the entire plane is relatively scattered. Especially, the rotor2 is most effected and the power loss may be increased, but the velocity distribution remains relatively stable at tilt angle of 30°.



40°



50°

Fig.13 Velocity cloud diagram at the speed of 4m/s.

In the Fig.13, when the horizontal wind speed is 4m/s, although the speed cloud image damage is more serious at the tilt angle of 50° than the tilt angle of 40°, the air velocity between the rotors has decreased and the power loss is possibly down. Therefore, power loading(PL) is biggest at the tilt angle of 50° and smallest at the tilt angle of 40°.

Conclusion

In this paper, the CFD method is used to verify the test results. After analysis and comparison, the conclusions are as follows:

Since the rotors of a non-planar hex-rotor aircraft can be tilted arbitrarily within a certain range, it form a face-to-face unit and a back-to-back unit between the two rotors, the speed of outflow and the aircraft of flexibility are improved, thereby improving aerodynamic performance and increasing thrust. Compared with the traditional plane hex-rotors aircraft, The thrust of non-planar hex-rotors aircraft has been greatly improved. In this study, the thrust of the non-planar hex-rotor aircraft is the largest when the inclination angle is 40°and the rotor speed of 2200r/min, which is about 75% more than the thrust of the planar hex-rotor aircraft at this time.

Under the influence of the horizontal wind, the thrust of the non-planar hex-rotor aircraft is reduced. The main reason is that the horizontal wind destroys the outflow of the face-to-face unit and the back-to-back unit and the vortex generated near the tip of the blade.

With the increases of horizontal wind speed, the aerodynamic interference to the aircraft also increases. However, for non-planar hex-rotor aircraft, the tilt angle of the rotor can be changed to adjust flight attitude and to resist aerodynamic interference. When the horizontal wind speed is 0m/s, 2.5m/s and 4m/s, the best inclination angle is 10°, 30°and 50°. At this time, the ability to resist wind disturbance is strongest. On the contrary, the worst inclination angle is 40°at the wind speed of 0m/s, 2.5m/s, 4m/s, and it shows poor resistance to wind disturbance.

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Author contributions

Y.L conceived and conducted the experiment(s), C.M implemented a set of simulation methods and analyzed the results, C.M and Z.F wrote the manuscript with assistance of Y.L. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.