Advances in Aerospace Science and Technology, 2024, 9, 28-39
https://www.scirp.org/journal/aast
ISSN Online: 2473-6724
ISSN Print: 2473-6708

Analysis and Research on Aerodynamic Characteristics of Quad Tilt Rotor Aircraft

Jike Jia, Xiaomei Ye, Guoyi He, Qingjin Huang, Zhile Hong

Faculty of Flight Engineering, Nanchang Hangkong University, Nanchang, China
Email: 70190@nchu.edu.cn

How to cite this paper: Jia, J.K., Ye, X.M., He, G.Y., Huang, Q.J. and Hong, Z.L. (2024) Analysis and Research on Aerodynamic Characteristics of Quad Tilt Rotor Aircraft. *Advances in Aerospace Science and Technology*, **9**, 28-39.
https://doi.org/10.4236/aast.2024.91003

Received: January 2, 2024
Accepted: March 11, 2024
Published: March 14, 2024

Abstract

For the quad tilt rotor aircraft, a computational fluid dynamics method based on multiple reference frames (MRF) was used to analyze the influence of aerodynamic layout parameters on the aerodynamic characteristics of the quad tilt rotor aircraft. Firstly, a numerical simulation method for the interference flow field of the quad tilt rotor aircraft is established. Based on this method, the aerodynamic characteristics of isolated rotors, rotor combinations at different lateral positions on the wing, and rotor rotation directions under different inflow velocities were calculated and analyzed, in order to grasp their aerodynamic interference laws and provide reference for the design and control theory research of such aircraft.

Keywords

Quad Tilt Rotor Aircraft, Analysis of Aerodynamic Characteristics, CFD Method

1. Introduction

A tiltrotor wing vehicle is a kind of vehicle that combines helicopter and fixed wing aircraft. It has advantages such as vertical takeoff and landing capability, large carrying capacity, strong endurance, and high cruise speed. It has a strong application prospect [1] [2]. The quad tilt rotor vehicles (QTR) adding a pair of wings and a pair of tiltrotors to a tiltrotor vehicle, the quad tilt rotor vehicles (QTR) has greater load capacity, better handling, and safety stability, although increasing structural weight. But the quad tilt rotor vehicles are more complex to construct than tiltrotor vehicles. In multiple flight regimes, there is interference between the rotors, wings, and fuselage, resulting in more complex aerodynamic interference problems [3] [4] [5]. Through research and analysis, we can master its aerodynamic interference law, which is of great help to the design of such aircraft, the research of control theory and the improvement of overall performance.

At present, there is much research on tiltrotors at home and abroad, tiltrotor is in its infancy, but some work has also been carried out. In the early years, Maisel [6] *et al.* conducted experimental studies on the aerodynamic characteristics of the XV-15 tiltrotor in hover and obtained the results of the variation of the wing surface loading distribution disturbed by rotor slipstream. Sheng *et al.* [7], predicted and analyzed the unsteady flow field and aerodynamic characteristics of a tiltrotor vehicle based on a sliding grid and reviewed experimental verification. Tianyu Chen [8] established a set of numerical calculation models for the aerodynamic characteristics analysis of a tiltrotor and used the momentum source method to conduct a steady full aircraft numerical simulation of its over-tilt state. Jinshuai Shi [9], using a body fitted grid combined with a rotor momentum source, analyzes the effects of tiltrotor aerodynamic configuration parameters on aerodynamic characteristics. Yongcheng Wu [10], aerodynamic analysis of tiltrotor using computational fluid dynamics method, rotor using momentum source method, steady numerical simulation of its over tilt state, and analysis.

Overall, there are not many studies on tiltrotor vehicles, and current CFD methods have the advantages of high accuracy, low relative cost, and the ability to effectively simulate flow details, and are an important method for studying the aerodynamic characteristics of tiltrotor vehicles. For this tiltrotor vehicle, a set of numerical methods suitable for the simulation of the interaction flow field between the rotor and wing of the vehicle is established using the multiple reference frame method, and the non structural grid is divided. The study analyzed the aerodynamic characteristics of an isolated rotor, with different lateral positions on the wing and different combinations of propeller installation directions, under various inflow velocities. It also explored the interference mechanism to provide a preliminary understanding and reference for improving the aircraft model in the future.

2. Models and Methods

2.1. Geometric Model and Mesh Division

The quad tilt rotor aircraft used in this paper is shown in **Figure 1** below. The front and rear wings and rotors of this model are of the same size and at the same horizontal height. Different from common tilting rotor models, this model adopts overall tilting of the rotors and part of the wings to avoid the “fountain effect” [11], which greatly improves the flight efficiency of tilting wing aircraft during vertical takeoff and landing.

In order to study the overall performance of the vehicle, the aerodynamic characteristics between the vehicle’s components must first be studied to provide a basis for further improvement of the type, the overall parameters of the vehicle and the parameters of the propeller are shown in **Table 1**.

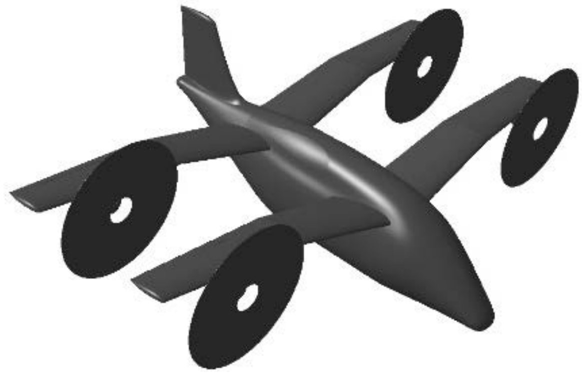

Figure 1. Quad tilt rotor aircraft geometry model.

Table 1. Main parameters of quad tilt rotor aircraft.

Parameter	Numerical value	Parameter	Numerical value
Fuselage length/m	7.25	Rotor airfoil	VR-5
Fuselage height/m	1.5	Rotor root cut/m	0.002
Fuselage width/m	1.35	Rotor speed/RPM	1600
Wing span/m	12	Rotor radius/m	1.45
dihedral angle of wing	10	Number of rotor blades	5

The front and rear wings and rotors of the type are of the same size, so the research object of this article is mainly component based, providing a basis for further improvement of the type, so all the research omits the fuselage, thus saving operations, such as performing separate rotor simulation operations, performing the same simulation operations for separate rotors and wings, and performing different rotor combinations for a pair of front and rear wings and rotors. The flow field calculation watershed used is a cuboid, about 15 times the length of its own size. The generation method of non structural grid is used, and the grid type is polyhedral grid. In order to restore flow details more realistically, the number of grid used is more than 10 million.

In order to fully simulate the flow of the wing and rotor boundary layer, it is necessary to generate a boundary layer mesh on the surface of the wing and rotor, so that y^+ is close to 1, and the calculation formula of y^+ is as follows: (1), so as to calculate the grid spacing of the first layer of the grid boundary layer. 15 boundary layer grids were generated, and the mesh growth rate was 1.2. And some details of the local encryption, so that the operation can be better convergence, to achieve better simulation effect, grid diagram as shown in **Figure 2**.

$$y^+ = \frac{u^* y}{\mu} \tag{1}$$

u^* is friction velocity near the wall, y is the distance between the first mesh node and the wall, and μ is the kinematic viscosity of the fluid.

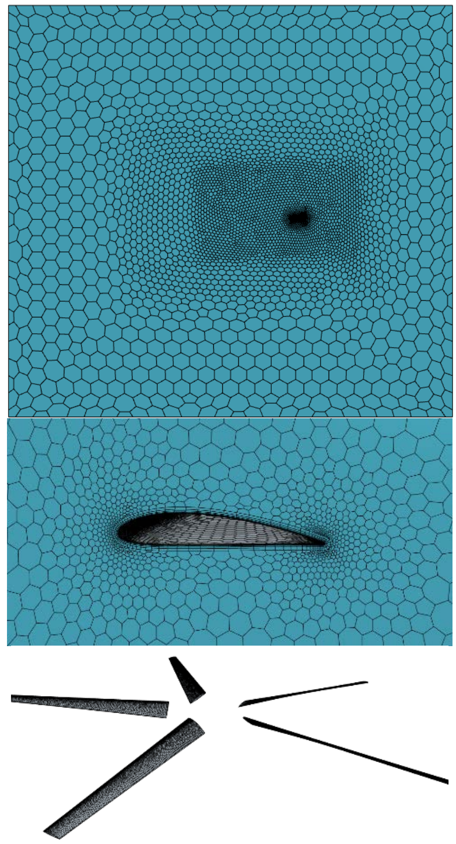

Figure 2. Computational domain grid and wing rotor surface grid.

2.2. Method of Calculation

Multiple reference frame is a common computational method, which is one of the simpler multi region computational methods. Different rotational or translational velocities can be assumed in different regions, and the transient problem is solved approximately as a steady state problem. If the region is at rest, the equation is transformed into the form of a stationary system. At the interface of the computational domain, a local reference frame is used to perform flux calculations of flow variables in one region and convert them to adjacent regions. The most important feature of the multiple reference frame method is that it can simulate the model directly, reflect the effect of the blades on the flow field more realistically, save computational resources relatively, and the results are more accurate.

In this paper, the aerodynamic characteristics of each part of the tilting quadrotor were simulated by solving Reynolds mean N-S equation. The turbulence model was selected as SSTK-ω model, the steady-state calculation was selected to solve the N-S equation, and the medium characteristics of the flow field were selected as ideal gas. The numerical solutions could be obtained more accurately through comparison. The quad tilt rotor aircraft calculated in this article has the same rotor specifications and front and rear wings. Therefore, the numerical calculation between components is carried out in this paper, and only one side is selected, excluding the fuselage.

The turbulence model is SSTK-ω model, according to reference [12], K is used to describe the change of turbulence energy, and the governing equation is as follows:

$$\frac{\partial}{\partial t}(k\rho)+\frac{\partial}{\partial x_j}(\rho u_j k)=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon \quad (2)$$

where ρ is the fluid density, k is the turbulent kinetic energy, u_j is the velocity component, μ is the dynamic viscosity, σ_k is the correction coefficient, μ_t is the turbulent dynamic viscosity, P_k is the turbulent energy generation term, and $\rho\varepsilon$ is the turbulent dissipation rate.

The Omega equation is used to describe the variation of turbulent dissipation rate, and the control equation is:

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}(\rho u_j\omega)=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\right]+P_\omega-C_{\lim}\rho\omega^2 \quad (3)$$

ω is the turbulent dissipation rate, σ_ω is the correction coefficient, P_ω is the turbulent dissipation rate production term, $C_{\lim}$ is the limiting factor.

2.3. Example Verification

This paper uses the rotor in reference [13] as an example to verify the multiple reference frame method. The main parameters of this type of rotor are shown in Table 2 below.

Figure 3 compares the calculated tension of an isolated rotor at different speeds with experimental values in the literature. Through numerical calculation, it can be seen that the rotor lift force obtained by the numerical simulation of multiple reference frame method is basically consistent with the experimental value on the whole, which can meet the needs of engineering calculation.

Table 2. Example rotor parameters.

Parameter	Numerical value
Number of rotor blades	2
Blade diameter	0.305
Rotor airfoil	Clark Y
Rotor root cut/m	0.305
Rotor pitch/m	0.14

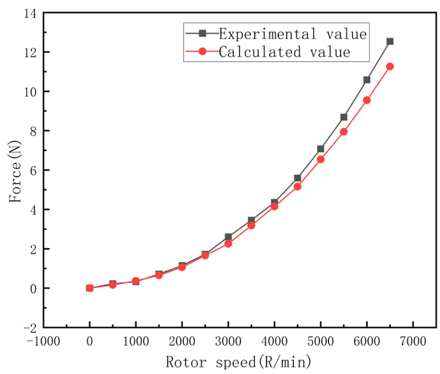

Figure 3. Comparison of the calculated and experimental values of the isolated rotor tension.

3. Results and Discussion

The quad tilt rotor aircraft calculated in this article has the same rotor specifications and front and rear wings. Therefore, the numerical calculation between components is carried out in this paper, and only one side is selected, excluding the fuselage [14].

3.1. Aerodynamic Characteristics of Isolated Rotors at Different Forward Speeds

This section carries out a study on the influence of an isolated rotor on its aerodynamic performance under conditions of different coaxial flow velocity. The rotor speed is 1600 RPM, and the axial flow velocity is 8 m/s, 15 m/s, 30 m/s, 45 m/s and 60 m/s respectively. This speed range includes the speed under all conditions from take-off to cruise. It provides the basis for further improving the propeller. Grid independence verification was carried out for a single rotor. The number of grids calculated for the first time was 5 million, the number of grids calculated for the second time was 10 million, and the number of grids calculated for the third time was 15 million, and the error of the three calculations was within 5%. **Figure 4** shows the force calculated for the three times of the rotor, and **Figure 5** shows the moment of force calculated for the three times of the rotor.

It can be seen from the data in the figure that with the increase of the axial flow speed, the tension of the rotor decreases sharply, and the torque of the rotor also decreases. This is because the initial flow velocity is small and the impact on the rotor is also small, which can even be ignored. The rotation speed of the rotor is enough to provide a large pull and torque. On the one hand, the performance of the rotor depends on the speed. As a result, the aerodynamic Angle of attack of the blade element is reduced, which leads to the reduction of the tension and torque of the entire rotor. Therefore, from the practical point of view, the pitch variation of the propeller needs to be considered in the real application, so as to achieve the best performance of the rotor.

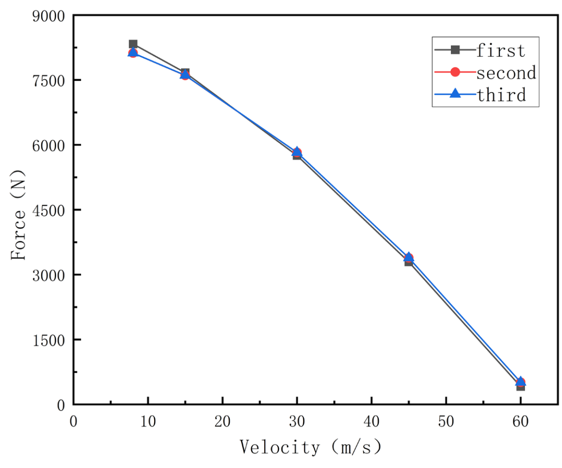

Figure 4. Rotor tension at different axial inflow velocities.

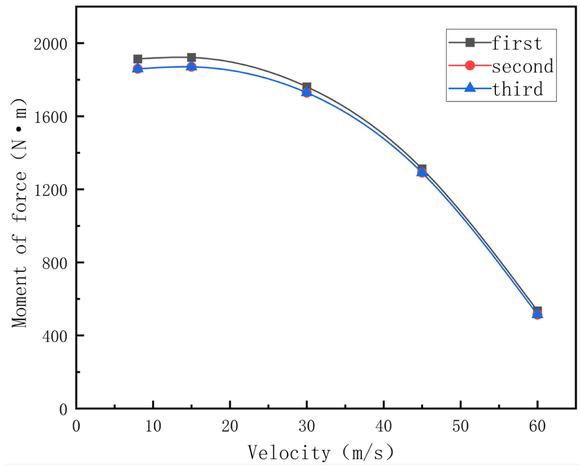

Figure 5. Rotator moment of force at different axial inflow velocities.

3.2. Research on the Influence of Aerodynamic Characteristics of Rotors at Different Lateral Positions on Wings

The study in this section is to determine the optimal lateral position of the propeller on the wing, so as to maximize the wing lift-drag ratio and minimize the performance loss during the roll. Since the front and rear wings and rotors have the same specifications, only the front wings and rotors are selected as the research object in this section. Start from the outermost position of the wing, that is, the position of the wing tip, which is recorded as the position of 0 m, start from the position of 0.5 m, and move closer to the position of the wing root in turn. Each position of 0.5 m is regarded as the position of a rotor, which is successively placed at the positions of 0.5 m, 1 m, 1.5 m 2 m, and 2.5 m, as shown in Figure 6 below.

The rotors are at different lateral positions on the wing, thus monitoring wing lift and drag, lift-drag ratio, and rotor force are shown in Figures 7, 8, and 9, respectively.

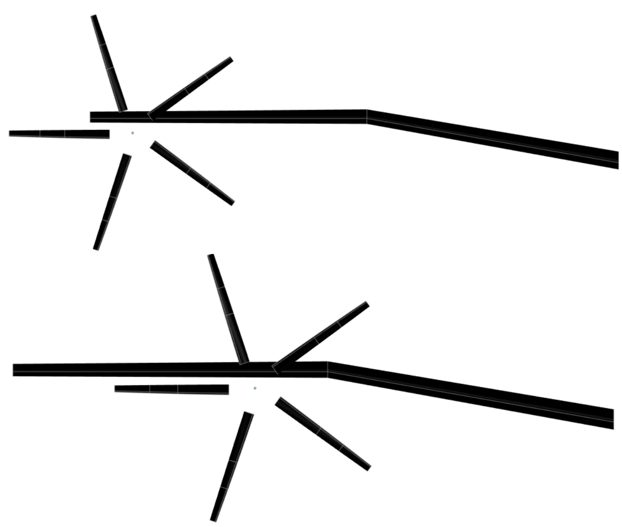

Figure 6. The rotor is located at 0.5m and 2.5m positions on the wing.

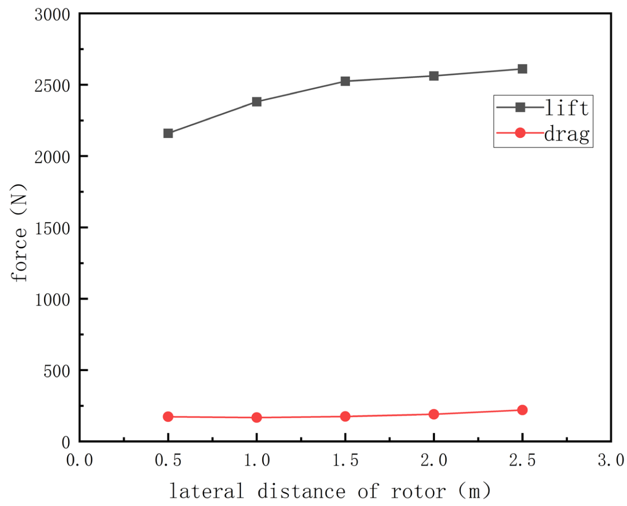

Figure 7. Wing lift and drag.

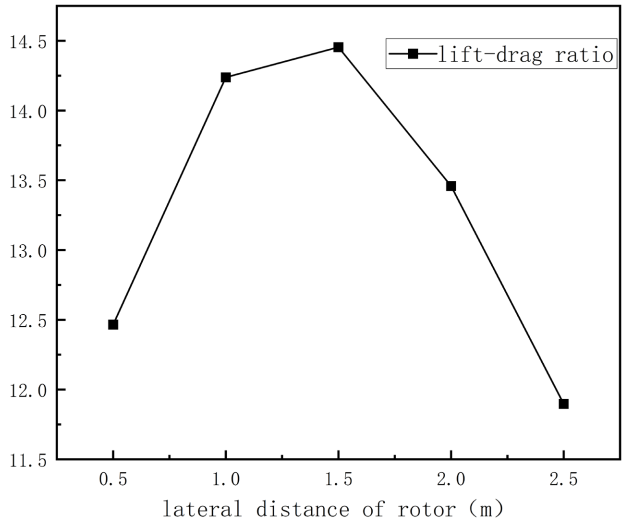

Figure 8. Wing lift-drag ratio.

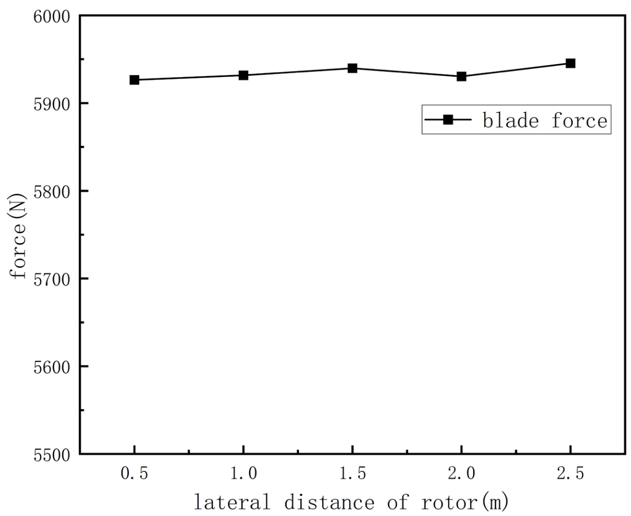

Figure 9. Rotor force.

From the above figure, it can be observed that as the rotor moves laterally towards the wing root, the lift of the wing gradually increases while the increase in drag is relatively small. This is because as the rotor gets closer to the wing root, the rotor's induced flow affects a larger area of the wing, resulting in an increase in the nearby airflow velocity, lift, and drag. Furthermore, from the above figure, it can be seen that although the lift of the wing increases as the rotor gets closer to the wing root, according to **Figure 8**, the maximum lift-to-drag ratio occurs when the rotor is positioned at $1.5m$ along the wing. Beyond 2 m the lift-to-drag ratio starts to decrease. This is because at 1.5 m, the rotor's induced flow affects the largest area of the wing, resulting in an optimal lift-to-drag ratio at that location. Due to the wing's shape, which has a certain amount of dihedral angle, and the tilt position of the rotor being at the mid-span of the wing, although the rotor at 2.5 m along the wing can provide a greater lift for the wing, during the tilting process, some of the rotor's downwash flow will act on the fixed section of the wing, resulting in the so-called "fountain effect."

Therefore, the rotor located at 1.5 m of the wing is the best position, which can not only provide the maximum lift-drag ratio, but also avoid the loss of aircraft performance during the tilt process.

3.3. Aerodynamic Characteristics of the Combination of Different Rotation Directions of the Rotor

The wing of tilting quadrotor aircraft will be affected by the rotor wake when flying forward, and the rotation direction of the rotor will directly affect the flow direction and speed of the air behind the rotor, which has a great influence on the pressure distribution and aerodynamic load on the wing. Therefore, it is necessary to study the influence of different rotor rotation layout on the aerodynamic characteristics of the whole aircraft. In order to balance the reverse torque, the rotation directions of the two rotors of the tilting quadcopter on the same wing surface should be opposite, so the rotation directions of the rotors are as shown in **Figure 10**. It is defined that the rotation direction of the rotors towards the wing root is as inward rotation, and the rotation direction towards the wing tip is as outward rotation. Therefore, group (a) means that the rotors rotate inward, group (b) means that the front rotors rotate inward and the rear rotors rotate outward, and group (c) means that the rotors rotate outward. Group (d) The front rotors turn outward and the rear rotors turn inward. In order to save computing resources, only the front and rear wings and rotors on one side of the fuselage are also selected to match, excluding the fuselage, and only the different rotation directions of the front and rear wings and rotors are calculated.

The effects of different rotor direction combinations on wing lift and rotor force are shown in **Figures 11** and **12**.

As can be seen from **Figure 11**, the front wing lift increases in spin combination (c) and spin combination (d). In both configurations, the front rotor rotates outward from the nose, while the rear wing lift increases in spin combination (b) and spin combination (c). In both configurations, the rear rotor rotates outward from the nose. It can be seen that the layout in which the rotor rotates outward on the wing can improve the lift of the wing to a certain extent, because the sliding flow of the propeller will increase the lift of the wing, and the left and right sides of the propeller will respectively produce upwash and downwash on the wing, among which the upwash is the main source of the increase in lift. Therefore, when the rotor rotates outward, the lift of the wing can be improved. The upwash produced by the rotor will produce a certain increase in the lift of the wing. As can be seen from **Figure 12**, the rear rotor tension increases in rotation combination (b) and rotation combination (d). In these two layouts, the rotation direction of the front and rear rotors is opposite, indicating that the front rotor rotation also has a certain influence on the rear rotor force.

From the above figure, it can be seen that the four rotors are arranged in a layout where the rotation directions of adjacent rotor positions are opposite and the rotation directions of diagonal rotor positions are the same, which improves both the tension on the rotor and the lift on the wing. Due to the influence of the rotor, there is a circumferential velocity in the wake of the rotor that is the same as the rotation direction of the rotor, resulting in an additional upward velocity component in the wing flow behind the rotor, which reduces the local wing profile inflow angle, increases the aerodynamic attack angle, and ultimately increases the lift of the entire wing, the same applies to the rotor.

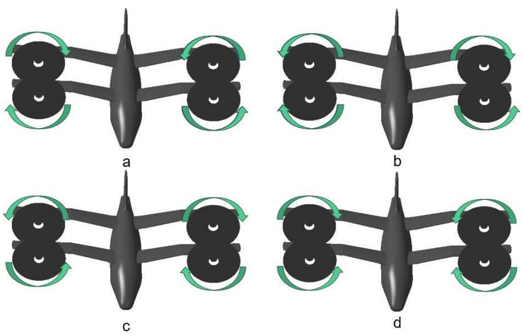

Figure 10. Rotor rotation combination.

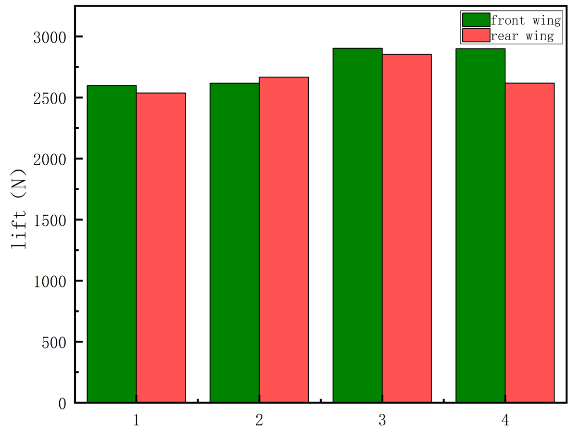

Figure 11. The effect of rotor rotation combination on wing lift.

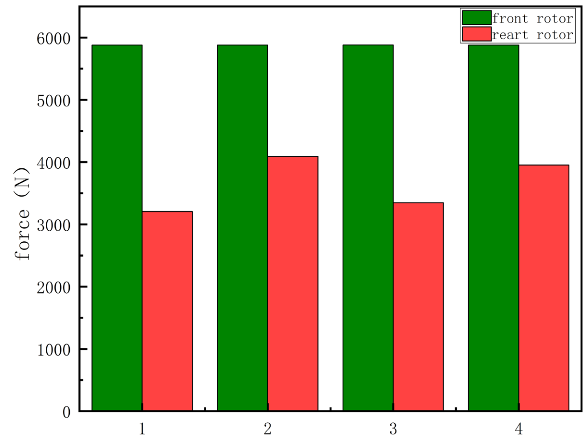

Figure 12. The effect of rotor rotation direction combination on rotor force.

4. Conclusions

Based on the multiple reference frame method, this paper analyzes the influence of aerodynamic layout parameters on the aerodynamic characteristics of the tilting quadrotor model, studies and analyzes the aerodynamic characteristics of the isolated rotor under different forward flight speeds, the combination of the rotor in different transverse positions of the wing and the rotor in different rotation directions, and draws the following conclusions:

With the increase of forward flight speed, the rotor aerodynamic force decreases obviously. In order to further optimize the design, variable pitch technology is needed.

The rotor is located at the lateral position of 1.5 m of the wing, which is the best position. The aerodynamic performance of the wing is greatly improved, and the interference of the rotor to the fixed section wing during the tilt is also reduced.

The quad tilt rotor aircraft are arranged in the opposite rotation direction of the adjacent rotors and the same rotation direction of the diagonal rotors, which is conducive to improving the lift of the wings and the aerodynamic performance of the whole aircraft.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 12362026).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zhao, G. (2019) Aerodynamic Interaction Analysis and Wing Optimization of Tiltrotor Aircraft. Nanchang Hangkong University, Nanchang, China.

[2] Wang, Y.C. (2022) Analysis of Aerodynamic Characteristics of Tilt-Wing UAV in the Transition Section and Influence of Multi-Rotor Wind Field Measurement. Nanchang Hangkong University, Nanchang, China.

[3] Liu, Y. (2019) Design of Tilting Device and Research on Transition Section of Tilting Wing UAV. Nanchang Hangkong University, Nanchang, China.

[4] Peng, P. (2021) Analysis of the Aerodynamic Characteristics of the Tilt-Wing UAV in the Transition Section of the Homeward Voyage Based on the Unsteady Method. Nanchang Hangkong University, Nanchang, China.

[5] Ren, J.X., Wang, Q., He, G.Y. and Liu, R.P. (2021) Modeling and Analysis of Heading Control in Vertical Take-Off and Landing Section of Tilting Wing UAV. *Technology Innovation and Application*, **11**, 1-5.

[6] Maisel, M. and Harris, D. (1981) Hover Tests of the XV-15 Tilt Rotor Research Aircraft. 1*st Flight Test Conference*, Las Vegas, 11-13 November 1981. https://doi.org/10.2514/6.1981-2501

[7] Sheng, C. and Narramore, J.C. (2009) Computational Simulation and Analysis of Bell Boeing Quad Tiltrotor Aero Interaction. *Journal of the American Helicopter Society*, **54**, Article 42002. https://doi.org/10.4050/JAHS.54.042002

[8] Cheng, T.Y., Xu, Y., Liang, Z. and Wang, H. (2020) Momentum-Source Method and Analysis on Aerodynamic Characteristics for Quad Tilt Rotor Aircraft in Conversion State. *Air Space Defense*, **3**, 17-22.

[9] Shi, J.S., Lin, M.Y., Zhang, X.Y., Zhao, Q.J. and Zhao, G.Q. (2022) Analysis of Aerodynamic Characteristics and Influence of Parameters of the Quad Tiltrotor Aircraft. *Flight Dynamic*, **40**, 1-7.

[10] Wu, Y.C., Chen, Z.L. and Ji, J.J. (2020) Quad-Tilt Rotor UAV Aerodynamic Characteristics. *Journal of Ordnance Equipment Engineering*, **41**, 72-75.

[11] Wang, Y.C., He, G.Y. and Wang, Q. (2022) Aerodynamic Performance Analysis and Optimization of Tilt-Wing UAV in Return Transition Section. *Science Technology and Engineering*, **55**, 9848-9856.

[12] Zhang, M., Xue, R., Pi, M. and Huang, W.P. (2014) Study on Application of the Modified $SSTK - \omega$ Model in Computation of Cloud Cavitating Flows. *HYDROCHINA Xibei Engineering Corporation*, *Xi'an* 710065, No. 4, 76-81.

[13] Wu, D.W., Li, H.B. and Li, S. (2011) Experimental Study of Static-Thrust Propeller for Mini-Vertical Takeoff and Landing (VTOL) Aircraft. *Journal of Aerospace Power*, **26**, 897-902.

[14] Chen, T.Y. (2018) Researches on Aerodynamic Design and Analyses on Aerodynamic Characteristics of a Quad Tilt Rotor Aircraft. Nanjing University of Aeronautics and Astronautics, Nanjing.