CFD simulation of rotor aerodynamic performance when using additional surface structure array

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**Abstract.** The present work analyses the aerodynamic performance of the rotor with additional surface structure array in an attempt to maximize its performance in hover flight. The unstructured grids and the Reynolds Average Navier-Stokes equations were used to calculate the performance of the prototype rotor and the rotor with additional surface structure array in the air. The computational fluid dynamics software FLUENT was used to simulate the thrust of the rotors. The results of the calculations are in reasonable agreement with experimental data, which shows that the calculation model used in this work is useful in simulating the performance of the rotor with additional surface structure array. With this theoretical calculation model, the thrusts of the rotors with arrays of surface structure in three different shapes were calculated. According to the simulation results and the experimental data, the rotor with triangle surface structure array has better aerodynamic performance than the other rotors. In contrast with the prototype rotor, the thrust of the rotor with triangle surface structure array increases by 5.2% at the operating rotating speed of 3000r/min, and the additional triangle surface structure array has almost no influence on the efficiency of the rotor.

1. **Introduction**

In the last few decades, the multi-rotor Micro-aerial vehicles (MAVs) 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 especially suited to perform missions considered tough, dirty, or dangerous [1, 2]. 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 study 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 [3]. As a result, the particular challenge of improving the aerodynamic performance lies in overcoming the various aerodynamic problems associated with low Reynolds number flight, which generally manifests as lower efficiencies and higher power consumption.

It has been studied by many researchers that good aerodynamic performance could be achieved through using surface structures. The riblet technology has been used on aircraft wings, which could provide a benefit to aerodynamic efficiency by reducing skin friction drag. The experiment by L.P.
Chamorro et al. [4] reported a reduction of roughly 6% in a turbine airfoil with riblets. The study by K.A. Seffen [5] shows that generating a surface texture in a shell of an airfoil section model can improve how the shell or structure interacts with the world around it, and the testing of similar specimens in a wind tunnel indicates that switching on the texture, at the correct wind speed, can reduce the drag significantly - as the dimples do on a golf ball. However, the additional surface structure array has never been tried on the rotor blade.

In this work, rotors with additional surface structure array are introduced to optimize the aerodynamic performance of the rotor. The computational fluid dynamics software Fluent is used to simulate the thrust of the prototype rotor and the rotor with additional surface structure array. Based on the accuracy of CFD results, surface structures in different shapes are being tried on the rotor blade. And the optimal rotor model is selected through CFD simulation. The purpose of this study is to propose a new design of the rotor blade used on the MAVs to improve the aerodynamic performance.

2. Numerical method

2.1. Parameters of the models

The prototype rotor in this paper is widely used on the MAVs, which is made of carbon fiber. The parameters of the prototype rotor are shown in Table 1.

Table 1. The parameters of the prototype rotor

| Model                       | Rotor       |
|-----------------------------|-------------|
| Number of blades            | 2           |
| Diameter                    | 17 inch     |
| Pitch                       | 5.8 inch    |
| Average blade chord         | 38 mm       |

In this study, the additional surface structure array used on the rotor blade is located on the specific area of lower surface close to the blade trailing edge. The parameters of the rotor with additional surface structure array are shown in Figure 1. The surface structure array on each blade consists of 8 triangle surface structures. The width of the triangle surface structure’s edge near the blade trailing edge ranges from 2 mm to 5 mm (2 mm ≤ L ≤ 5 mm), and the height from 7 mm to 17 mm(7 mm ≤ H ≤ 17 mm). The thickness of all the surface structures is 1 mm (T=1 mm). The spacing between the two adjacent surface
structures is 10 mm (D=10 mm). The radial distance between the rotor center and the surface structure closest to the central axis is 134 mm (0.62R).

2.2. Calculating method and boundary conditions
Simple method and Reynolds Average Navier-Stokes k-ε viscous model are used to get the solution of RNS equation in this paper. The unstructured grids are used in the meshing of the rotor, for it can use optional shape elements as the control region, which have characteristics of well skin quality and self-adaptation [6, 7]. The mesh distribution of the rotor with additional surface structure array is shown in Figure 2. The Cartesian coordinate system is set up: X coordinate is the same with the blade’s radius line; Z coordinate is the direction of outlet flow, which presents consistency with the rotated axis of the rotor; Y coordinate complies with the rule of right-handed.

![Image](image)

**Figure 2.** The mesh distribution of the rotor with additional surface structure array

This work takes the cylinder as the control volume. The mesh is the unstructured triangle elements. The positions of inlet and outlet are respectively two and three times of the rotor’s diameter from the position of the rotor. The position of the outer boundary is two times of the rotor’s diameter from the axis of the hub. The boundary conditions include velocity inlet, pressure outlet, and RNG k-ε viscous model. The thrusts of the rotors are calculated at the rotating speed of 2000r/min, 2200r/min, 2400r/min, 2600r/min, 2800r/min and 3000r/min, respectively.

3. Results and analysis

3.1. Preliminary calculation and experimental validation
This study has a preliminary research on the calculation of the rotor with additional surface structure array, and proposes a new way to improve the aerodynamic performance of rotors used on the MAVs.

With the potential theory, the lifting body moves in the flow field, it must produce a trailing vortex surface [8]. When calculating the aerodynamic performance of the rotor with additional surface structure array, the wake of this rotor is different from that of the prototype rotor, and it’s difficult to predict the influence. It’s believed that the more the real practical calculating model is used, the more precise pressure distribution of the rotors can be predicted.

This study has firstly calculated the thrusts of the prototype rotor and the rotor with additional triangle surface structure array in open air. In order to validate the results of the numerical simulation, experiments are carried out on the thrust test platform. The triangle surface structures are made through 3D printing, and fixed on the designed location of the rotor blade.
The thrusts of the rotor with triangle surface structure array and the prototype rotor are measured at different rotating speeds. The CFD calculation and the experiment results of the two rotors are shown in Figure 3.

![Figure 3](image-url)  
**Figure 3.** Thrust of the prototype rotor and the rotor with additional surface structure array

Obviously, the experimental data are in reasonable agreement with the numerical simulation results, and the calculation error is confined in the allowable range. It indicates that the thrust of the rotor with triangle surface structure array is greater than that of the prototype rotor at the same rotating speed. That is to say, the rotor with triangle surface structure exhibits better aerodynamic performance. Compared with the prototype rotor, the thrust of the rotor with triangle surface structure array increases by 5.2% at the operating rotating speed of 3000r/min.

According to the experiment results, the correlation between Power consumption and Thrust showed in Figure 4 can prove that additional surface structure array has almost no influence on the efficiency of the rotor. On the other hand, the results in Figure 3 show that the calculation model used in this paper is correct.

![Figure 4](image-url)  
**Figure 4.** The correlation between power consumption and thrust
3.2. Simulation of rotors with arrays of surface structure in different shapes

Using this theoretical calculation model, the thrust of the rotor with arrays of surface structure in different shapes are calculated in this study. As shown in Figure 5, the shape of surface structure is changed into streamline and tetrahedron, respectively.

![Figure 5. Rotors with arrays of surface structures in two different shapes, (A) the rotor blade with streamline surface structure array, (B) the rotor blade with tetrahedral surface structure array.](image)

The simulation thrust of the rotor with arrays of surface structure in different shapes and the prototype rotor are shown in Figure 6.

![Figure 6. The simulation results of the rotor with surface structures in different shapes and the prototype rotor](image)

According to the results of the simulation, it could be obviously observed that the rotor with triangle surface structure array has the prior on aerodynamic performance than the other rotors do. And the optimal rotor model is the rotor with triangle surface structure array. The pressure distributions of the rotors calculated in this paper are shown in Figure 7. It could be seen that the pressure of the rotor with triangle surface structure array is higher than that of the other rotors. This is in agreement with the experimental results. The pressure distributions show that the surface structures have the capability of improving the aerodynamic performance of rotors, and the rotor with triangle surface structures achieves the best performance among these rotors. The pressure distribution at the location where surface structures are fixed shows that the surface structures could improve the rotors' wake, and the airflow near the trailing edge of the modified rotors is better than that of the prototype rotor. Itʼs supposed that the surface structure array could cause more turbulence near the trailing edge, which has a beneficial effect on pressure distribution. The surface structure array could make the pressure distribution at the
trailing edge stronger, and the triangle surface structure array could make the pressure distribution in the most regions of the lower surface stronger. The results of simulations clearly indicate that the design of using additional surface structure array could achieve better aerodynamic performance.

Figure 7. The pressure distribution of the rotors, (A) pressure distribution of the prototype rotor, (B) pressure distribution of the rotor with triangle surface structure array, (C) pressure distribution of the rotor with streamline surface structure array, (D) pressure distribution of the rotor with tetrahedral surface structure array.

4. Conclusion
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 its limitations arising from aerodynamic issues. This paper provides a new design of rotor with additional surface structure array.

The CFD software Fluent is used to simulate the thrusts of the prototype rotor and the rotor with triangle surface structure. Compared with the experimental data, the calculated results are in good agreement with the experiments and the errors are allowable. The results indicate that the calculation model used in this work is correct. Using this theoretical calculation model, the thrusts of the rotor with arrays of surface structure in different shapes are calculated.

The numerical simulation shows that the rotor with triangle surface structure array has better aerodynamic performance than the prototype rotor and the rotors with surface structures in streamline and tetrahedral shape. And the experimental data prove that the rotor with triangle surface structure array shows better aerodynamic performance than the prototype rotor. In contrast with the prototype rotor, the thrust of the rotor with triangle surface structure array increases by 5.2% at the operating rotating speed of 3000r/min. The additional triangle surface structure array has almost no influence on the efficiency of the rotor, for the power consumption of the rotor with triangle surface structure array is almost the same as that of the prototype rotor at the same thrust.

The method of using additional surface structure array on rotor blade is effective in improving the aerodynamic performance of rotors. In the future, the parameters of surface structure array could be optimized, including the spacing between two adjacent surface structures, the distribution position of the array and the three-dimensional size of surface structures.
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