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Experimental and Numerical Investigation of Propeller Shape Effect on Aircraft Aerodynamic Performance

Libo Li, Jian Chen, Hongcheng Han, Mengfan Zhang, Xutun Wang, Qiuwang Wang*

Key Laboratory of Thermo-Fluid Science and Engineering, MOE, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, P.R. China
wangqw@mail.xjtu.edu.cn

Propeller is the crucial component of the fixed-wing aircraft. It provides thrust for fixed-wing aircrafts and has a great influence on the aerodynamic performance and carrying capacity of fixed-wing aircraft. For motor-driven micro-sized fixed-wing transport aircraft, the propeller needs to cooperate well with the motor to achieve high propulsion efficiency. In order to obtain the optimal design of propeller, experimental and numerical investigation was carried out and compared with three kinds of propeller. The tailor-designed propeller was proposed under specific conditions. Tailor-designed propeller better fits with the motor in the flight of the aircraft, improving the efficiency of the propellers, and increasing the carrying capacity of the aircraft. According to the characteristics and working conditions of the aircraft and the working characteristics of the motor obtained from the experiment, the aerodynamic shape of the propeller is initially designed based on the leaf theory and Betz conditions, then the parameters are continuously adjusted based on the numerical simulation results, and the results with the best performance are selected as the final result. Comparing the numerical simulation results and experimental results of tailor-made propellers and existing propellers under design conditions, the results show that, with the same power absorbed by the motor, the tailor-made propeller can provide greater thrust. The increase in thrust means that the aircraft can overcome greater resistance and generate greater lift, which improves the carrying capacity of aircraft. Numerical simulation and test flight methods were used to explore the impact of thrust improvement on aircraft lift and carrying capacity.

1. Introduction

The technology of propellers is strongly associated with the development of aircraft. Propellers constitute the predominant means of propulsion for the small fixed-wing aircrafts (Alba et al., 2018). Compared with the turbojet propulsion systems, propeller propulsion systems exhibit low energy consumption, high efficiency and low cost. With the development of electric motor, more and more micro fixed-wing aircraft adopt the propeller-driven propulsion. Under the circumstance that the motor power is limited and the flight state of the aircraft is clear, a high-efficiency propeller is of great significance for improving the performance of the aircraft. So, the study of propeller has attracted more attention recently in engineering.

The aerodynamic theory of propeller has undergone a continuous development. In 1952, Lerbs put forward the propeller lift line theory, which can be used to analyse the performance of sweepback propeller. Fan et al. (2018) put forward a nonlinear correction method of the standard strip analysis. Morgado et al. (2015) presented the design procedure and the optimization steps for a new propeller to be utilized at high altitude. Dorfling et al. (2015) presented a procedure for deriving the Euler-Lagrange equations for both unconstrained and constrained propeller blade-twist optimisation. Xiang et al. (2018) presented an improved design method for propeller of an electric aircraft. Premkumar et al. (2019) studied the performance of micro-aerial vehicle propeller.

The blade angle and chord distribution are the main factors that control the performance of propellers. In this paper, in order to get a better aerodynamic performance of a propeller, a novel design method is proposed. The numbers of propeller blades, propeller installation method and propeller diameter are selected according to the working conditions and the characteristic of the engine. The radial distribution of the propeller's chord length and blade angle was calculated based on the Betz condition theory. Standard strip analysis is conducted to optimize the geometric shape of the propeller, which avoids the limit of the Betz condition theory of propellers’

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design. Finally, the aerodynamic performance of the propeller designed by the new method is analysed and verified by numerical simulation and tunnel experiment.

2. Calculation methods of propeller performance

The calculation of propeller performance is an essential process in propeller design as well as an important factor to the evaluation of the propeller design. An efficient and accurate calculation method of propeller performance is of significant importance in propeller design.

The momentum theory and blade element theory are simple and facile in the existing aerodynamic theories of propeller. However, their accuracy is poor. The lift line theory and lift face theory, which have high accuracy, are not suitable for rapid iterative calculation due to the large amount of calculation, long calculation cycle and complicated calculation process. It's why the standard strip analysis, which has high accuracy and a faster calculating speed, was used to calculate the propeller performance in this paper.

2.1 The standard strip analysis

The basic calculation process of standard strip analysis is as follows. First, preset v_0 (Airspeed), D (Diameter), n (Rotational speed), θ (Blade angle), N_B (Blade number), b (Blade element chord length). Calculate v_t (Circumferential speed), φ_0 (Geometric angle of attack) and σ (Solidity of blade elements). Then calculate C_l (Lift coefficient) and C_d (Drag coefficient) of each blade element in a certain range of Mach number and angle of attack, and compute the β (Interference angle) by Newton iteration method. Calculate the φ (Actual inflow angle), a (Axial speed interference factor), a' (Circumferential speed interference factor), T_C (Thrust factor), P_C (Power factor). Lastly, integrate the result of each blade element along the radius and calculate the T (Thrust), P (Power) and η (Efficiency) of the whole propeller.

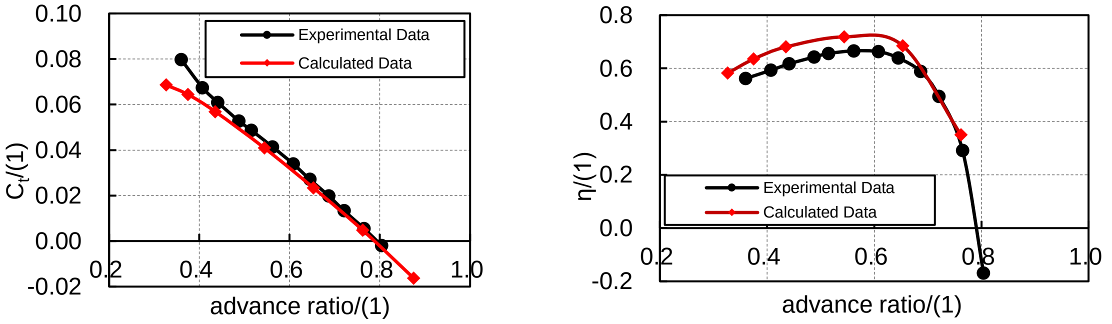
$$T = \frac{1}{2}\rho v_0^2 N_B \int_{r_0}^{R} T_C dr \tag{1}$$

$$P = \frac{1}{2}\rho v_0^2 N_B \int_{r_0}^{R} P_C dr \tag{2}$$

$$\eta = \frac{Tv_0}{P} = \frac{v_0 \int_{r_0}^{R} T_C dr}{\int_{r_0}^{R} P_C dr} \tag{3}$$

2.2 The verification of standard strip analysis

To verify the accuracy of the standard strip analysis, write the MATLAB code in Section 2.1. Select a propeller which has been tested in wind tunnel, calculate its performance by the MATLAB code and plot its C_t (Thrust Coefficient) and η (Efficiency) curves of calculated results and wind tunnel results, as shown in Figure 1. The aerodynamic characteristic data of airfoil was calculated by the Xfoil.



(a) Change of C_t with advance ratio *(b) Change of efficiency with advance ratio*

Figure 1: Changes of C_t and efficiency with advance ratio

Figure 1a and Figure 1b show that the calculated results of thrust coefficient are similar to wind tunnel experimental results when the advance ratio is between 0.4 and 0.8, and the efficiency is highest when advance ratio is about 0.6. From the point of view of obtaining the propeller thrust and the maximum efficiency point, the average deviation of the results of C_t in experimental data and calculated data is less than 5 %, and the average deviation of the results of efficiency in experimental data and calculated data is less than 8 %, which indicates that this calculation method can meet the demand of both accuracy and speed.

3. Propeller geometry design

3.1 Basic parameters of propeller

Both the output power of engine and the airplane's flight conditions should be concerned about when determining the basic parameters of propeller. In this project, the brushless electric motor is used to provide torque for propeller and the revolving speed of motor can be changed by using the ESC. The cruising speed of the airplane is 12 m/s and the flight height is below 50 m. In this project, the output power of motor is about 130 W after considering the heat loss and the revolving speed of propeller is about 6,300 r/min.

The propeller can be divided into fixed-pitch propeller and variable-pitch propeller. The airplane of this project has a high requirement for weight control and the mechanism, which can adjust the pitch, will bring much extra weight and affect the reliability. It's the reason why the fixed pitch propeller is selected. The fewer the blades the more efficient is the propeller. To improve the efficiency, N_B was determined to be two parameters. There is an equation which is of some help in choosing the propeller diameter as the power of motor (Hitchens, 2015):

$$D=\sqrt[4]{\frac{P}{n^2\times V_0\times 24.8}}\times 245 \tag{4}$$

After calculating and considering the limit of Mach number of blade tip, D was determined to be 0.305 m.

The small fixed-wing UAV propellers must have good aerodynamic characteristics at low Reynolds number because they generally work in the range of low Reynolds number (Koichi et al., 2016). To simplify the model, the propeller designed in this project adopted only one airfoil and the transition treatment of the geometry was carried out at the blade root. The Reynolds number at the relative radius of 0.7 is about 70,000. The airfoil E193, shown in Figure2, which has ideal lift and drag characteristics at low Reynolds number was selected. Its C_l and $C_l{\cdot}C_d^{-1}$ curves are shown in Figure 3.

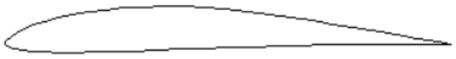


Figure 2: E193 airfoil

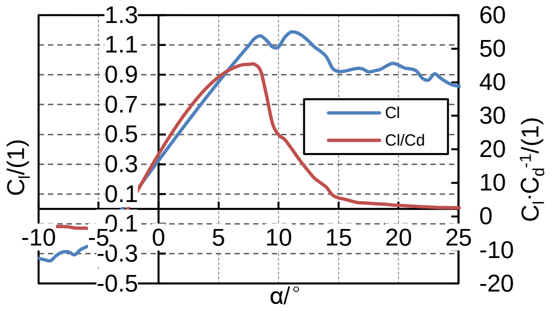


Figure 3: The C_l and $C_l{\cdot}C_d^{-1}$ data as a function of angle of attack

3.2 Original data of blade element chord length and blade angle

The Betz condition is a common method for designing the propeller. Compared with the numerical solution method, it is convenient and time-saving. By using the Betz condition and the parameters in Section 3.1, the original data of blade element chord length and blade angle can be calculated easily, shown in Figure 4.

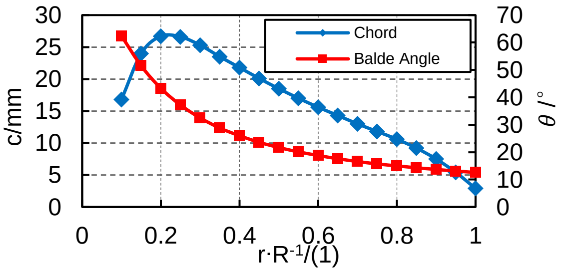


Figure 4: The original chord length and blade angle distribution

3.3 Optimization of the standard strip analysis

The Betz condition isn't considering the effect of airfoil loss and Mach number and when considering the influence of air viscosity, the resistance caused by the viscosity of the blade will change the optimal ring quantity distribution of the propeller. It's why the original chord length and blade angle of blade elements ought to be optimized. To simplify the model, only the chord length will be optimized by the standard strip analysis in this project. Based on the original result in Section 3.2, the chord length will change within a certain range. The aerodynamic performance of the new propellers will be calculated soon and the geometry, which has the highest efficiency under the premise that the power does not exceed the maximum output power of motor, will be selected finally. The process is illustrated in Figure 5.

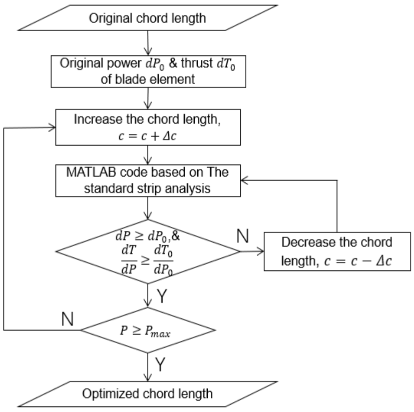


Figure 5: Optimization flow chart

As shown in Figure 6, contrasting the original and optimized chord length of propeller blades, the viscosity effect and the drag of blade element let the chord length distribution move inward, the chord length in the middle area increases, and the plane shape of the blades become full. As shown in Table 1 decreasing the chord length at the root of blade appropriately and increasing the chord length at the middle and tip of blade can improve the aerodynamic performance of original propeller.

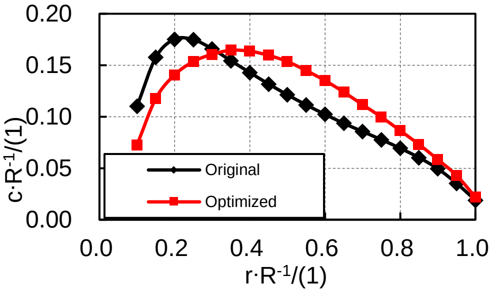


Figure 6: Comparison of optimized and original chord length distribution

Figure 7: The optimized geometry of propeller

Table 1: The aerodynamic performance of the original and optimized propeller (at 12 m/s and 6,300 rpm)

	Original	Optimized	Improved performance
Thrust/N	5.99	6.98	16.53 %
Power/W	106.48	121.05	13.68 %
Efficiency/%	67.51	69.19	1.68 %

4. Simulation and test

4.1 Numerical simulation method

1) Numerical solution method

In order to obtain the aerodynamic characteristic parameters of the propeller accurately, CFD numerical simulation was carried out for the propeller. The MRF method in the CFD numerical simulation was utilized. By solving the steady flow field of the propeller, the thrust and torque of the propeller was obtained. In CFD numerical simulation, a professional mesh generation software ICEM CFD was used to generate mesh and realize the mesh assembly which was then imported to FLUENT to carry out the solution.

2) Mesh generation

A professional mesh generation software ICEM CFD is used to generate mesh of the flow field based on hybrid mesh method. The flow field is divided into two parts: the rotating field surrounding the propeller and the fixed field. The rotating field adopts the unstructured mesh with the number of 2,000,000, and the fixed field adopts the structured mesh with the number of 700,000. The unstructured mesh in the rotating field can better adapt to the shape of the propeller and improve the mesh generation efficiency and applicability. The mesh of the leading edge and the tip of propeller is encrypted. After the network continues to be encrypted to twice the original number, the calculation results of thrust and torque change less than 1 %, so it is considered to pass the grid independence verification.

3) Results analysis

In the simulation, SST model was selected, which has a good computational accuracy for the simulation of rotating mechanical parts. Atmospheric conditions are the standard atmospheric conditions of sea level. Figure 8 shows the comparison of propeller characteristic curves obtained by different methods.

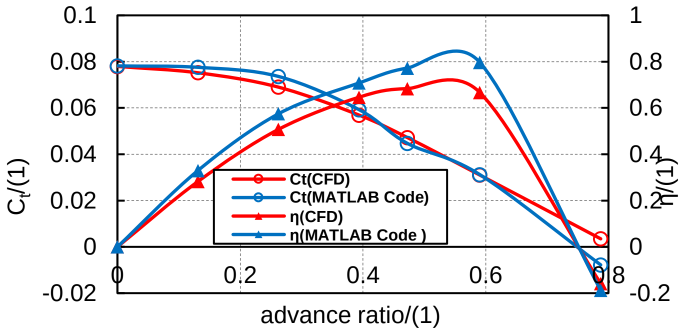


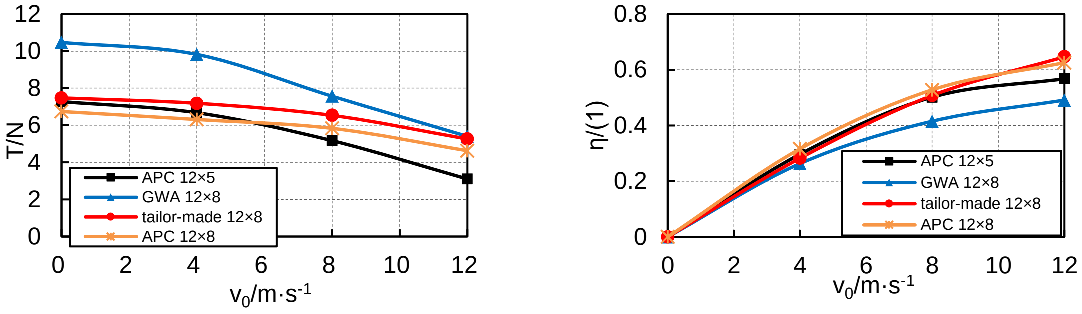
Figure 8: Propeller characteristic curves obtained by different methods

The MATLAB program relies on theory and empirical formulas for analysis, while the finite element analysis uses a discrete method and relies on a turbulence model for solution. The propeller characteristic curves described by these two methods agree with each other in the overall trend. In terms of value, the average relative error of the two Ct curves is 4.0 %, and the average relative error of the two efficiency curves is 13.1 %. The error is within the acceptable range for design. The analysis results can explain to a certain extent that the design and analysis theory and simulation analysis method are relatively reliable.

4.2 Wind tunnel test

In the wind tunnel test, the optimized propeller and three other propellers commonly available in the market were tested. The results are shown in Figure 9.

The design requirement is to achieve higher propeller efficiency under cruise conditions while meeting the thrust requirements of takeoff and cruise. In other words, increasing the carrying capacity of the aircraft as much as possible without changing the power consumption is the objective. As shown in Figure 9a and 9b, the propeller thrust meets flight requirements. Compared to APC12×5, the larger pitch makes tailor-made propellers have better high-speed performance, and the thrust attenuation decreases with the increase of the aircraft airspeed. Compared with APC12×8, tailor-made propeller achieves comparable efficiency under greater thrust, which is more conducive to improve the carrying capacity. Compared with GWA12×8, a more reasonable blade chord length distribution makes tailor-made propeller at the sacrifice part of static thrust can achieve considerable thrust and higher efficiency in cruise state.



(a) Thrust-airspeed curve at 6,000 rpm

(b) Efficiency-airspeed curve at 6,000 rpm

Figure 9: Results at 6,000 rpm

4.3 Flight performance analysis

The optimized propeller was installed on the aircraft for flight test. The flight performance of the aircraft was compared with the test flight results of APC12×8, which has the best performance in commodity propellers. As shown in Table 12, in the case of the same motor power, tailor-made propeller improves the aircraft's thrust-to-weight ratio and improves the aircraft's carrying capacity.

Table 2: Comparison of flight performance between different propellers

Heading 1	APC 12x8	Tailor-made 12x8	Variation
Thrust-to-weight ratio	1.79 (1)	2.00 (1)	11.73 %
Maximum capacity	1.38 kg	1.51 kg	9.42 %

5. Conclusions

- In this study, the experimental and numerical investigation was carried out to optimize the design of propeller. Three kinds of propeller are experimentally and numerically investigated, and a novel design method of propeller has been proposed based on these data.
- Propeller designed by the novel method can provide more thrust, enable the aircraft overcome more drag, generate more lift, and ultimately improve the flight performance of the aircraft, comparing with propeller designed by traditional method.
- Aircraft fitted with propellers designed by new design method increased thrust-to-weight ratio by 11.73 % and reduced carrying capacity by 9.42 %, comparing with traditional aircraft.

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