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STUDY ON THE EFFECTS OF PROPLET GEOMETRIC PARAMETERS ON THE AERODYNAMIC CHARACTERISTICS OF HIGH-ALTITUDE PROPELLER

Bo Wang[1], Xudong Yang[1], Bifeng Song[1]& Jianhua Xu[1]

[1] School of Aeronautics, Northwestern Polytechnical University, Xi'an, China

Abstract

Propeller is an important part of high-altitude airship propulsion system operating at low Reynolds number, which makes its aerodynamic performance, especially efficiency, influences the overall design of airship a lot. This paper intends to increase the efficiency by adding two different kinds of proplet, and a trade study of proplet geometric parameters is performed. A new parametric method of proplet geometry is developed. Reynolds Averaged Navier-Stokes (RANS) equations are adopted to examine the performance of baseline and propeller with proplet. And a power matching method developed in previous study is used to compare the efficiency under the same shaft power. The results show that proplet can increase the aerodynamic efficiency of high-altitude propeller. The upward-bend proplet can increase more aerodynamic efficiency than downward-bend proplet with the same geometric parameters by 0.7% in average. Height of proplet, incline angle and twist angle of proplet tip have prominent effect on efficiency. As the incline angle increasing, the efficiency can increase nearly 1.2% at most. Some of the geometric parameters of different kind of proplet have opposite influence as the values change.

Keywords: High-Altitude Propeller; Proplet; Low Reynolds Number; Efficiency Improvement

1. General Introduction

High altitude long endurance airship and unmanned aerial vehicle have been widely used in telecommunications, Earth observation science and other services [1]. In order to meet the demand of long-time spot hovering, the speed of airship is so slow that propeller nearly becomes the only choice of propulsion system. However, operating at such low air density and speed causes nonlinear aerodynamic characteristics because of laminar separation, making the propeller face the problem of low aerodynamic efficiency, which leads to effort to improve its performance. But there is upper limit when using conventional propeller configuration optimization method, for the flow characteristics remain unchanged. Under this circumstance, flow control method is a good choice to solve the problem. Research of applying active flow control, such as Co-Flow Jet [2] and plasma [3], etc. to propeller have been studied, but they are too complicated to manufacture in practice in near future. Therefore, passive flow control based on proplet is introduced to improve the aerodynamic efficiency.

The idea of proplet is enlightened by winglet proposed by Whitcomb, R.T in 1970s. Winglet improve aerodynamic performance by weakening the weak of wing tip, so that the induced drag decreases. In 1980, Irwin, K. and Mutzman, R. [4] conducted a research using the vortex theoretical and experimental methods to confirm the potential of proplet on improving the efficiency. Results show the proplet could increase the efficiency by about 1%, and the increment was associated with the proplet height. Chang and Sullivan [5] optimized the twist angle of propeller and its proplet using the vortex lattice method in 1984. They concluded that the proplet could improve the efficiency by 1~6%, compared with the baseline propeller. In 1989, proplet was introduced to aircraft propeller operating in high subsonic cruise flow of M=0.8 by Valaerzo [6]. In 2006, Sullivan [7] firstly applied proplet to the model airplane propeller. Theoretical analysis concluded that the proplet could increase the aerodynamic efficiency by 10% at most, while it didn't agree well against the experimental results. In recent years, our research team proceeded the study of prplet applied on near space propeller [8][9][10], and systematically examined the impact of some parameters on the aerodynamic efficiency. Based on previous studies, this paper conducts a trade study of some new parameters of proplet for two kinds of proplet respectively in order to improve the performance of high altitude near space propeller.

2. Methodology

2.1. Parametric Method of the Proplets

A parametric method is introduced in this paper, whose schematic is shown in Figure 1. And the geometric characteristics of proplet are uniquely determined by parameters including: height of the proplet *H*, chord length of proplet root and tip c_r, c_t, twist angle of proplet tip α_t, sweep back angle of proplet leading edge Λ_l and incline angle of proplet β_i. A transition part is added between proplet root and position of 98.5% baseline propeller span, which is small in size compared with proplet so that its geometry is not studied in this paper.

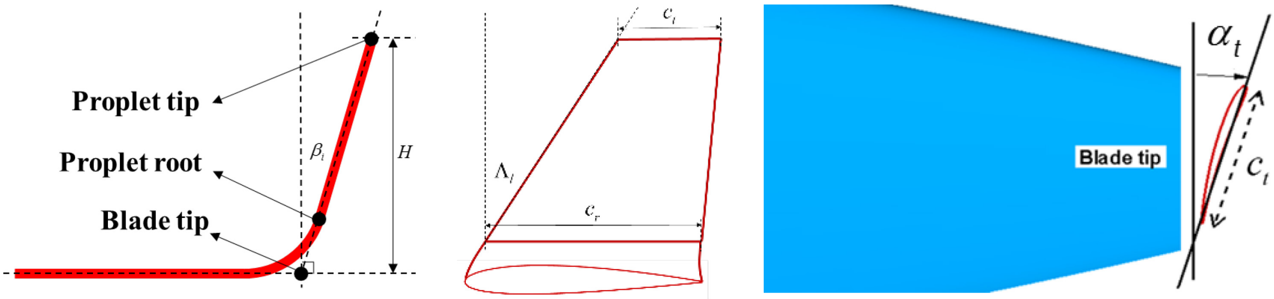


Figure 1 – Schematic of parametric method of the proplets

In addition, upward-bend and downward-bend proplets are studied in this paper, and Figure 2 shows the two kinds of proplet configuration compared with the baseline propeller. Moreover, the geometric parameters definitions of these two configurations of proplet are the same.

(a)Upward-bend proplet (b)Baseline (c)Downward-bend proplet

Figure 2 – Comparison between baseline and two kinds of propeller with proplets

2.2. Numerical Method

2.2.1. Governing Equations

The integral form Navier-Stokes equations for viscous flow can be written as follow:

$$\frac{\partial}{\partial t}\iiint_{\Omega}\mathbf{Q}dV + \iint_{\partial\Omega}\mathbf{F}\cdot\mathbf{n}dS - \iint_{\partial\Omega}\mathbf{F}_v\cdot\mathbf{n}dS = 0 \tag{1}$$

where $\mathbf{Q}$, $\mathbf{F}$ and $\mathbf{F}_v$ are flow conservation variable, inviscid flux vector and viscous flux vector, respectively. Ω and $\partial\Omega$ are the control volume and the boundary of control volume. When the flow velocity is perpendicular to the propeller disk, which is the operating condition of propeller in this paper, the flow is quasi-steady in the rotating coordinate frame fixed on the propeller. Therefore, it is more convenient to solve the flow around the blade when applying the N-S equation in the rotating coordinate frame, and it can be written as follow:

$$\frac{\partial_r}{\partial t}\iiint_\Omega \mathbf{Q}_r dV + \iint_{\partial\Omega} \mathbf{F}_r \cdot \mathbf{n} dS - \iint_{\partial\Omega} \mathbf{F}_{vr} \cdot \mathbf{n} dS + \iiint_\Omega \mathbf{G}_r dV = 0 \quad (2)$$

where

$$\mathbf{G}_r = \left[0, \rho(\boldsymbol{\omega}\times\mathbf{q}_r)_{xr}, \rho(\boldsymbol{\omega}\times\mathbf{q}_r)_{yr}, \rho(\boldsymbol{\omega}\times\mathbf{q}_r)_{zr}, 0\right]^T \quad (3)$$

$\boldsymbol{\omega}$ and $\mathbf{q}_r$ denote the angular velocity vector and the fluid velocity vector in the rotating coordinate frame. The cell-centered finite-volume method is applied to solve the governing equation, and the SST $k-\omega$ turbulence model is adopted.

2.2.2. Computational Grid

Considering the flow in present study is quasi-steady, only one of the blades is simulated to reduce the time consumption, while the influence of other blades can be obtained by the rotational symmetric boundary conditions. Multi-block pitch grid is applied to the simulation, and the computational domain consists of one rotational domain and one static domain, whose radius are two and ten times of the propeller diameter respectively, as shown in Figure 3.

Both domains apply H-H type grid. The grid near the blade surface is locally refined, and the relative thickness of layer near the wall satisfy the requirement '$y^+ \approx 1$' proposed by the SST $k-\omega$ turbulence model. The grid in wake zone of the blade is also refined in order to resolve the tailing vortex structure well. Figure 4 show the surface grid of overall blade and details of the grid around.

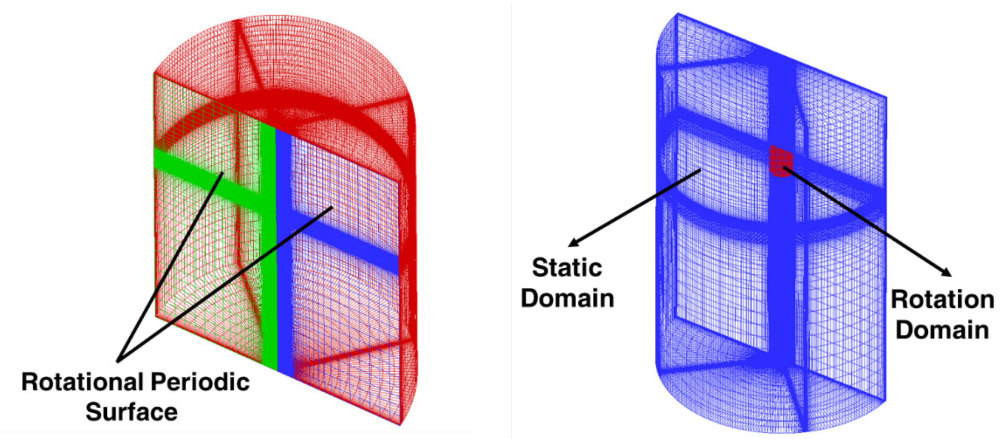


Figure 3 – Schematic diagram of the multi-block pitch grid

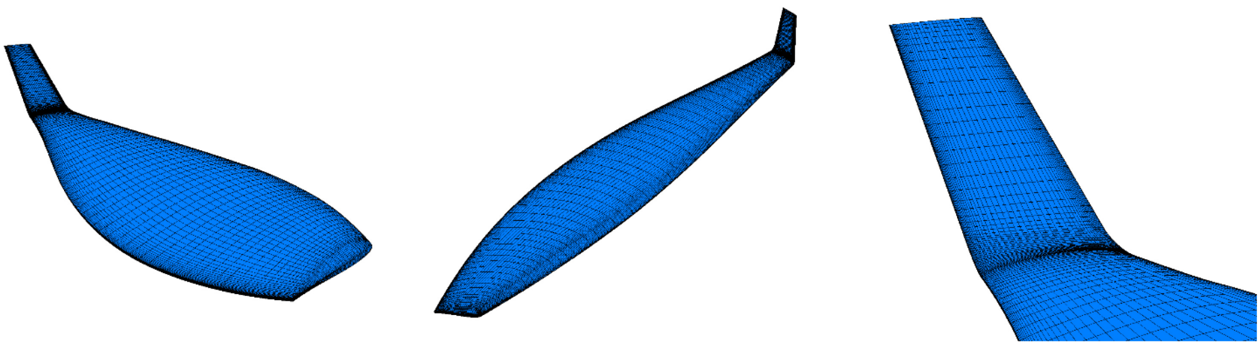


Figure 4 – Details of the grid on the blade surface

2.3. Power Matching Method

As one of the important characteristic of propeller, the limit of power absorbed is generally given at the beginning of design process. Then other parameters, which includes diameter, rotation speed, distribution of chord length and twist angle, will be adjusted to make the blades satisfy the limit of maximum power absorbed. After the geometric parameters are determined, the rotation speed and pitch angle can be adjusted to absorb the power as much as possible under the limited torque. In this study, the power absorbed is fixed in order to compare the aerodynamic efficiency of the propeller, so the power matching method proposed in previous research is adopted, which is based on Newton Iteration.

According to literature [10], the relationship between power and rotation speed is shown as follows:

$$P_s = C_{Ps}\rho_\infty n_s^3 D^5 \tag{4}$$

$$P_s' = \frac{\partial P_s}{\partial n_s} = \frac{\partial C_{Ps}}{\partial n_s}\rho_\infty n_s{}^3 D^5 + 3C_{Ps}\rho_\infty n_s{}^2 D^5 \tag{5}$$

the equation of Newton Iteration can be written as:

$$n_s(k+1) = n_s(k) - \frac{P_s - P_{s0}}{P_s'} \tag{6}$$

where P_{s0} is the power to be matched. In previous study, example of propeller with large power and small power are simulated respectively. The results show that the calculated power can convergent to required power within steps, which validated the competence of power matching method.

3. Results and Discussion

3.1. Validation of the Numerical Method

In this chapter, the CFD method mentioned above will be validated against the experimental results of a 1.2m diameter two-blade propeller. The wind tunnel experiments are carried out in the three-dimensional test section of the NF-3 low-speed wind tunnel at Northwestern Polytechnical University, as shown in Figure 5.

Atmospheric condition of this wind tunnel test is as follow: the air density $\rho_\infty = 1.109\,kg/m^3$, the atmospheric pressure $P_\infty = 0.97\times10^5 Pa$. Operating condition of the propeller is as follow: wind speed equals to 13m/s, range of rotation speed is from 800 to 2500 rpm. Taking chord length at the position of 75% span as the reference length, the Reynolds number varies from 2.5×10^5 to 8×10^6 as the rotation speed increases. The total mesh size is about 3.2×10^6.

Figure 6 and Figure 7 show the aerodynamic characteristics of 1.2m diameter propeller from CFD simulation, and they agree well against the experiment measurement, which can validate the competence of the aerodynamic analysis method to properly simulate the flow around the blade.

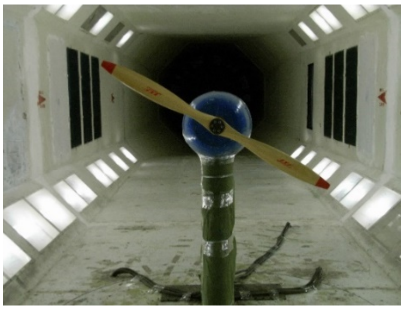


Figure 5 – Model of 1.2m diameter propeller (NF-3 wind tunnel of Northwestern Polytechnical University)

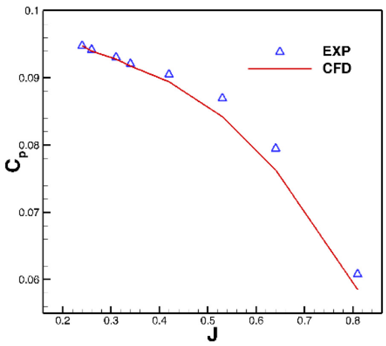


Figure 6 – Experimental and CFD results of the propeller (Coefficient of power)

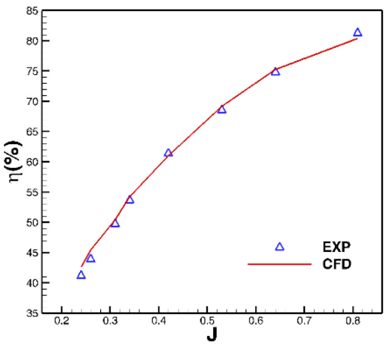


Figure 7 –Experimental and CFD results of the propeller (Aerodynamic efficiency)

3.2. Comparison Study of Propeller with and without Proplet

The baseline is a 7m-diameter propeller with two blade, and the design point status is as follow: the operation altitude is 20km, the wind speed equals to 10m/s, the power absorbed is 10kW, and the rotation speed is around 370 rpm. Geometric parameters of upward-bend and downward-bend proplets are the same, which are shown in Table 1, and the airfoil of proplet is NACA0012. Furthermore, this set of parameters will be chosen as the baseline of proplet in the trade study below.

Table 1 – Geometric parameters of proplets

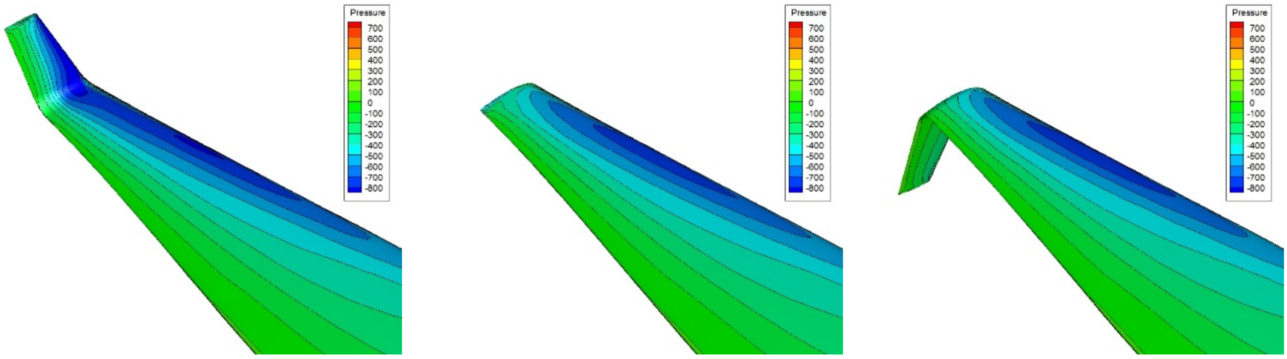
Height H/R	Incline angle $\beta_i\left(\circ\right)$	Twist angle $\alpha_t\left(\circ\right)$	Sweep angle $\Lambda_l\left(\circ\right)$	Root chord length c_r / c_{bt}	Tip chord Length c_t / c_{bt}
0.06	10	5	25	0.9	0.6

The mesh size of baseline and propeller with proplet are 5.1×10^6 and 5.8×10^6 respectively. The power matching method mentioned above is adopted to adjust the power absorbed equals to 10kW in order to compare the aerodynamic efficiency between baseline and propeller with proplet. The comparison results are listed in Table 2. It indicates that the proplet increase the aerodynamic efficiency by at least 0.62%(absolute value), which shows the potential of proplet in improving aerodynamic characteristics.

Figure 8 shows the pressure contours of the baseline propeller and the propeller with proplet. It can be observed that there is larger area of low pressure on the upper surface of latter, which leads to higher thrust when their shaft power is the same. Figure 9 show vorticity iso-surface of the baseline and propeller with proplet. It can be seen that the vortex induced by blades with proplets is shorter than baseline, which denotes the proplet can weaken the trailing vortex and inhibit the downwash of the wake. For these reasons above, the proplet can be an option to increase the efficiency of propeller.

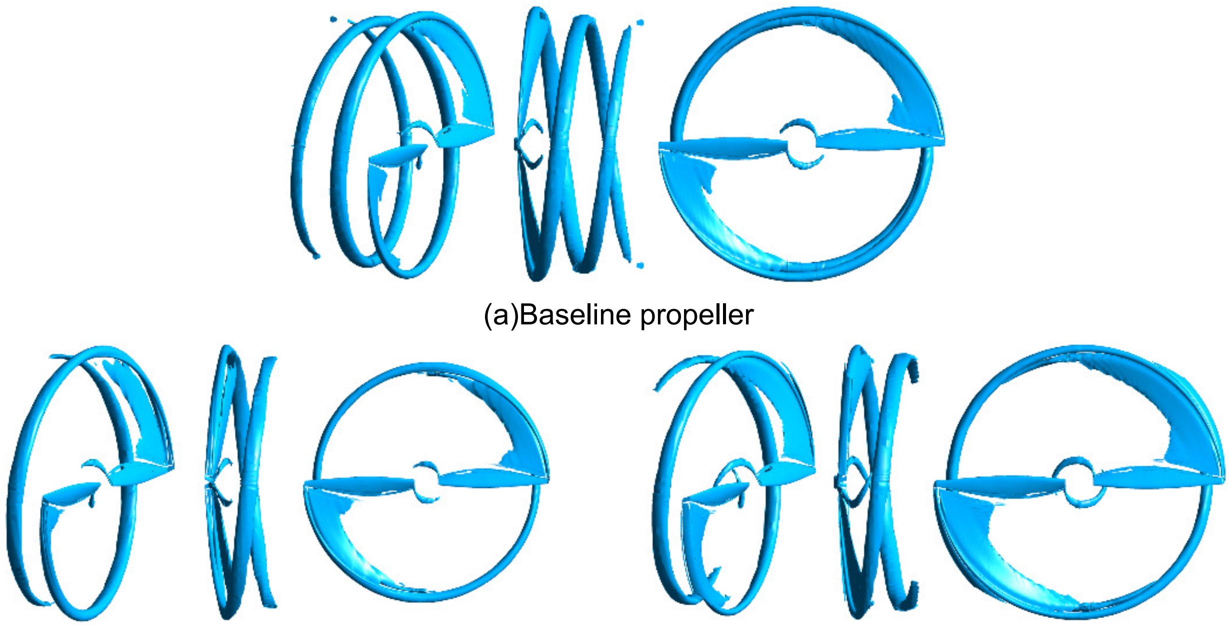
Table 2 – Comparison results of baseline and propeller with proplets

Configuration	Baseline propeller	Propeller with proplet	
		Upward-bend	Downward-bend
Aerodynamic efficiency	54.86%	55.86%	55.48%



(a)Propeller with upward-bend proplet (b)Baseline propeller (c)Propeller with downward-bend proplet

Figure 8 – Pressure contours of the baseline and propeller with proplets



(a)Baseline propeller

(b)Propeller with upward-bend proplet (c)Propeller with downward-bend proplet

Figure 9 – Vorticity iso-surface of the baseline and propeller with proplet

3.3. Trade Study of Proplet

In this section, six geometric parameters proposed above will be studied to find out the variation rules of propeller efficiency as they change. When the influence of one geometric parameter is studied, the others remain unchanged for the reason of variable control. The upward-bend and downward-bend proplets will be investigated at the same time.

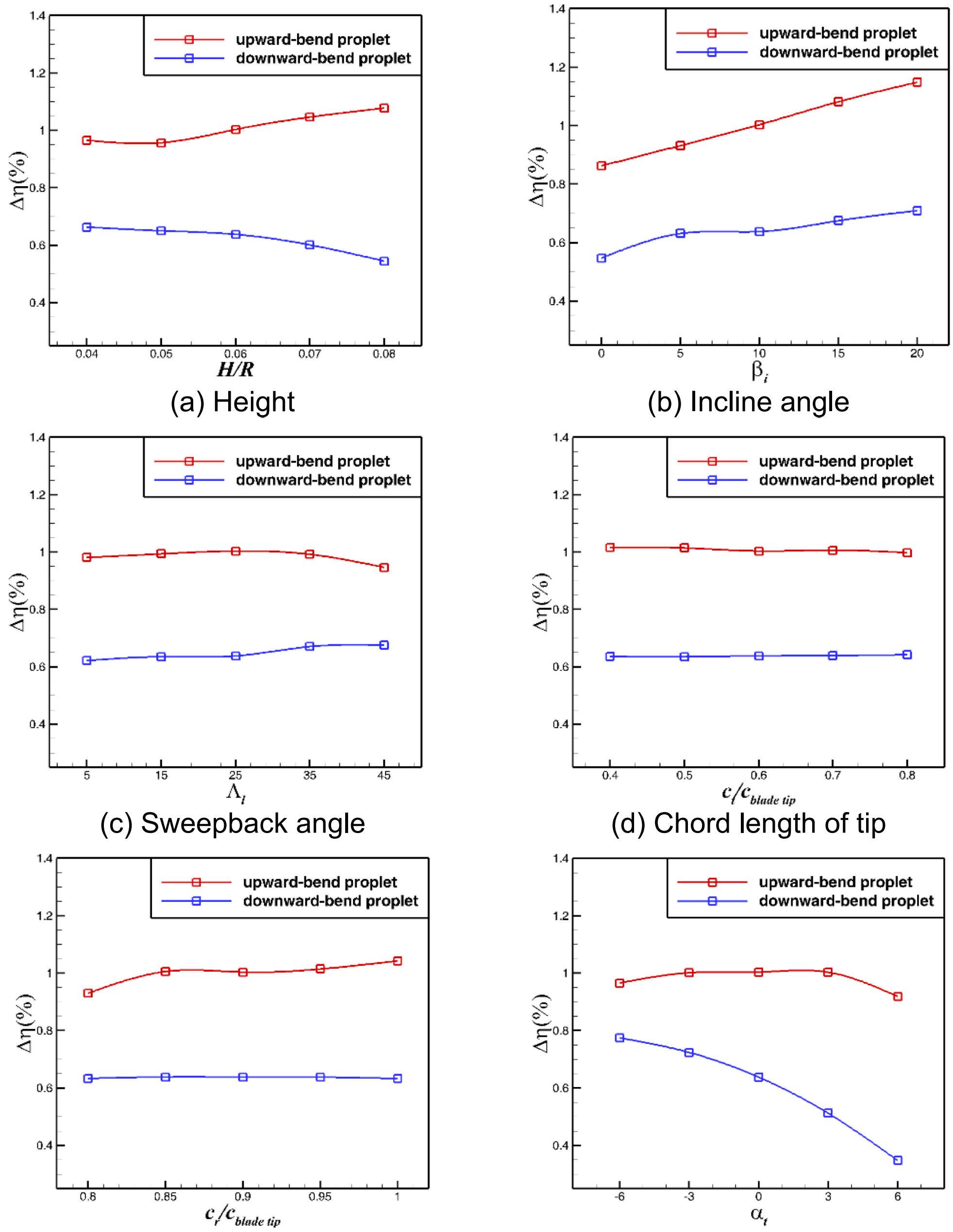
Figure 10 shows the effect of the geometric parameters on the aerodynamic efficiency of the propeller. It can be seen that the variation of chord length of proplet tip has almost no influence on aerodynamic efficiency of propeller, but the other parameters have more or less effect to some extent. Some of the parameters have the same influence trend on efficiency for both two kinds of proplet as they vary, taking incline angle for example. However, some have opposite influence, such as height. In addition, the upward-bend proplet always lead to higher aerodynamic efficiency compared with downward-bend proplet with the same geometric parameters.

As the height of proplet increase, the upward-bend proplet make the efficiency increase by 1.08%(absolute value) at most. On the other hand, the smallest height of downward-bend proplet leads to the most increment. As mentioned above, the incline angle can increase the efficiency of propeller for either kind of prolet, and in this group, the upward-bend proplet with incline angle $\beta_i = 25°$ contributes the most increment of efficiency $\Delta\eta = 1.15\%$, while the downward-bend one can only increases 0.56%. For sweep angle of leading edge, there seems to be a peak of efficiency increment in the variation range, and the peak for upward-bend proplet is around 25° while for downward-bend is between 35° and 45°. The efficiency of propeller is not sensitive to root chord length of downward-bend proplet in current range, but when the c_r / c_{bt} decreases to 0.8, the efficiency increment of upward-bend proplet drops rapidly. Figure 10(f) indicated the twist angle of downward-bend proplet tip has the most prominent influence on increasing efficiency, and the increment is up to 0.77% when α_t equals to -6°, which is the most efficiency increment of downward -bend proplet in this study. However, for upward-bend proplet, the value is less sensitive ,and is better to be kept between -3°~3°.

According to the discussion above, the design criteria of both two kinds of proplet can be concluded as follow:

- The upward-bend proplet should be designed with larger height and incline angle, medium sweepback angle (about 25°) and nearly 0° twist angle on the tip;

- The downward-bend proplet should be designed with smaller height, large negative twist angle of tip and sweepback angle between 35° and 45°.



(a) Height (b) Incline angle

(c) Sweepback angle (d) Chord length of tip

(e) Chord length of root (f) Twist angle of tip

Figure 10 – Effect of the geometric parameters on the aerodynamic efficiency of the propeller

4. Conclusion

In this paper, two kinds of proplet is proposed to improve the aerodynamic efficiency of propeller. A parametric method is developed to determine the geometry of proplet. RANS equations and multi-block pitch grid are adopted to resolve the details of flow structure, and a power matching method developed in previous study is used to make the shaft power equal in order to compare the efficiency.

According to the simulation results, the efficiency of propeller with proplet is higher than baseline, which indicates the proplet has positive effect. The reason is that proplet can weaken the trailing vortex and inhibit the downwash of the wake.

Six geometric parameters of upward-bend and downward-bend proplets are investigated to find out their variation rules against the efficiency. Results show that upward-bend proplet can increase more aerodynamic efficiency than the other kind of proplet by 0.7% in average when the parameters are the same. Height of proplet, incline angle and twist angle of proplet tip are prominent parameters. As the incline angle increasing, the upward-bend proplet can increase the efficiency by nearly 1.2% at most, which is the largest increment in this study. Some parameters of proplet have opposite effect on aerodynamic efficiency. And the preliminary design criteria are proposed.

5. Contact Author Email Address

Xudong Yang: xdyang@nwpu.edu.cn

6. Copyright Statement

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