Aerodynamic Performance of Variable-Pitch Propellers for High-Altitude UAVs

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Abstract. As the air density changes dramatically from high to low altitude, the matching of high-altitude propeller and electric motor under low-altitude condition is one of the main challenges that aerodynamic design of high-altitude propeller faces. To solve this problem, variable-pitch propeller is the most commonly used and feasible solution. In this paper, the Reynolds-average Navier-Stokes solver and an efficient surrogate-based optimization toolbox are used for the aerodynamic design of a fixed-pitch propeller. Based on the optimal fixed-pitch propeller, a series of pitch angle are employed to obtain the variable-pitch propeller with maximum thrust. Then, the aerodynamic characteristics of fixed-pitch propeller and variable-pitch propeller under typical working conditions are studied and compared. The results show that under the condition of low-altitude and low wind speed, the fixed-pitch propeller reaches the rated torque of the electric motor at a lower rotational speed, resulting in a lower shaft power and thrust. By adjusting the pitch angle, the variable-pitch propeller can achieve higher rotational speed under the same rated torque constraints, thereby absorbing more shaft power and achieving larger thrust. The lower the altitude, the more obvious the advantage of the variable-pitch propeller. Compared with fixed-pitch propeller, the maximum relative increment of the maximum thrust can reach more than 80% for variable-pitch propeller. It is concluded that variable-pitch propeller can significantly improve the matching of propeller and electric motor, bringing wider flight envelope of UAVs.

1. Introduction

Propellers are widely used in high-altitude vehicles including airships[1][2] and unmanned aerial vehicles[3] (UAVs). One of the challenges in the design of aerodynamic components for high-altitude vehicles is low air density. At the altitude of 20km, the atmosphere density is 7.25% of that on the ground, and the air density at 25km is only 3.27% of that on the ground. Under such atmospheric condition of low density, the propeller propulsion system is currently the only available power system for low speed aircrafts. Due to the low air density, the working Reynolds number of high-altitude propellers is very low[3], usually less than 300,000. In this range of Reynolds number, the aerodynamic performance of the airfoil may change severely with Reynolds number, which results in the deterioration of the airfoil’s aerodynamic performance (typically around the Reynolds number of 100,000) and decrease of the propeller efficiency.

Another key problem of the high-altitude propeller design is the matching of propeller and electric motor under low altitude. When the high-altitude propeller is used at a low altitude, where the air density is much higher than that at a high altitude (above 10km), the maximum rotational speed of the
propeller is lower due to the restriction of the maximum torque, resulting in a lower shaft power and thrust. A common and available technic to improve the matching of propeller and electric motor is variable-pitch propeller. With the pitch angle of propeller blade decreased, the effective attack angle of propeller section, lift and drag all decrease, and meanwhile the rotational speed, shaft power and thrust increase. The variable-pitch propeller has already been widely used in the large transport airplane. However, the problem of matching the electric motors at high and low altitudes is more urgent in the propeller design of high-altitude aircrafts.

This article studies the aerodynamic performance of the fixed-pitch propeller and the variable-pitch propeller. A baseline propeller (fixed-pitch propeller) is obtained by surrogate-based optimization, whose design point is under high altitude working condition and design target is highest efficiency. Then, the variable pitch propellers are obtained under a series of off-design conditions, with the angle of pitch decided by maximum thrust. The aerodynamic performances of the fixed-pitch propeller and the variable-pitch propeller are compared, followed by an analysis of the aerodynamic advantages of the variable-pitch propeller.

2. RANS solver for propeller

The integral form of Reynolds-averaged Navier-Stokes (RANS) equations expressed in the blade-attached rotational frame can be written as follows:

\[
\frac{\partial}{\partial t} \int \int \int_\Omega Q dv + \int \int_\Omega \mathbf{F} \cdot \mathbf{n} dS - \int \int_\Omega \mathbf{F}_v \cdot \mathbf{n} dS + \int \int \int_\Omega G dv = 0
\]  

(1)

where, \( t \) is time, \( \Omega \) and \( \partial \Omega \) stand for control volume and the corresponding boundary, respectively. \( dS \) and \( dv \) are elemental area and volume of the control volume, respectively. \( \mathbf{n} \) is the outward unit normal. \( Q \) is the conservation fluid variables. \( \mathbf{F} \) and \( \mathbf{F}_v \) are the inviscid and viscous flux term, respectively. \( G \) is the Coriolis force term.

The cell-centered finite-volume method proposed by Jameson[4] is used to solve the above governing equations on the chimera grid, and an in-house RANS solver, named ROTNS is developed. An improved Newton-like LU-SGS method[5] is utilized for time stepping, and a high-efficient FAS multi-grid method[6] on Chimera grid is developed to improve the computational efficiency. Jameson’s central scheme (JST)[4] is adopted for the spatial discretization scheme. Spalart-Allmaras (S-A)[7] one-equation model is used for turbulence enclosure.

The 2-bladed propeller with a diameter of 6 inches is simulated to validate the solver. This propeller model is designed by Wichita State University and tested in their 3ft × 4ft Low Speed Wind Tunnel[8]. The blade pitch angle that is represented by the angle at 75% of the blade radius ranges from 15° to 30°. The Reynolds number based on chord at 75% of the blade radius is within the range of 90,000 to 120,000 when the rotational speed is fixed at 6000rpm. Figure 1 shows the propeller shape with a blade pitch angle of 15°. Figure 2 demonstrates that results of the thrust coefficient, power coefficient and efficiency against the advance ratio by ROTNS are in good agreement with the experimental results.

![Figure 1](image-url)  
**Figure 1.** The 2-bladed propeller with a diameter of 6 inches and a blade pitch angle of 15°.
2. Results of the thrust coefficient, power coefficient, and efficiency against the advance ratio by ROTNS are in good agreement with the experimental results [8].

3. Aerodynamic design optimization of propeller

Based on an in-house surrogate-based optimizer, “SurroOpt” [9] [10], an aerodynamic design platform for the propeller is established, as shown in Figure 3.

Typical distributions of chord length and twist angle for a propeller are shown in Figure 4. The distribution functions are parameterized by quadratic function. According to the geometrical characteristic of the chord length distribution, the distribution function is defined by two quadratic functions split at the maximum chord length point, which can be written as:

\[
C_R = \begin{cases} 
  a_1 (x - x_{c_{\text{max}}})^2 + C_{R_{\text{max}}} & x \leq x_{c_{\text{max}}} \\
  a_2 (x - x_{c_{\text{max}}})^2 + C_{R_{\text{max}}} & x > x_{c_{\text{max}}} 
\end{cases}
\]

in which,

\[
a_1 = \frac{C_{R_{\text{root}}} - C_{R_{\text{max}}}}{(x_{\text{root}} - x_{c_{\text{max}}})^2}, a_2 = \frac{C_{R_{\text{tip}}} - C_{R_{\text{max}}}}{(x_{\text{tip}} - x_{c_{\text{max}}})^2}
\]

where, \(C_s\) is the chord length of blade section, \(x\) is the radial coordinate, \(x_{c_{\text{max}}}\) is radial coordinate at maximum chord length point, \(C_{R_{\text{max}}}\) is the maximum chord length, \(C_{R_{\text{root}}}\) is the chord length of blade root section, \(x_{\text{root}}\) is radial coordinate at blade root section, \(C_{R_{\text{tip}}}\) is the chord length of blade tip section, \(x_{\text{tip}}\) is radial coordinate at blade tip section.

The distribution of the twist angle can be written as a general form of following quadratic function:

\[
\beta = a_{\beta} x^2 + b_{\beta} x + c_{\beta}
\]

where, \(\beta_s\) is the twist angle of blade section, \(a_{\beta}, b_{\beta}\) and \(c_{\beta}\) are coefficients of the function.

Moreover, at the blade tip (\(x>0.8\)) the chord length and twist angle are kept as a constant, and the blade section is translated by \(ds\) along the chord direction, which is defined as

\[
ds = a_s (x - x_s)^2
\]

in which, \(a_s = \frac{ds_{\text{tip}}}{(x_{\text{tip}} - x_s)^2}\)

where, \(ds_{\text{tip}}\) is the translation length at the blade tip. \(x_s\) and \(x_{\text{tip}}\) are the starting radial location and the blade tip radial location. In this article, \(x_s\) is fixed to 0.8 and \(x_{\text{tip}}\) is 1.0.
Therefore, the 8 design variables of the geometry parameterization are $x_{\text{max}}, C_{R_{\text{max}}}, C_{R_{\text{root}}}, C_{R_{\text{tip}}}, a, \beta, b, c$, and $ds_{R_{\text{tip}}}$. 

4. Variable-pitch propeller

The pitch angle $\Delta \theta$ of the fixed-pitch propeller is defined as 0 (Figure 5), while the pitch angle of variable-pitch propeller can be adjusted according to the working conditions of UAVs. Using the altitude and wind speed of the fixed-pitch propeller at cruise condition as baseline, the principle of the variable-pitch propeller is given as follows.

For higher altitude and wind speed, the rotational speed reaches the rated value first, while the torque and the shaft power are lower than rated value. Therefore, a positive pitch angle ($\Delta \theta > 0$) is employed to increase the torque and shaft power at the rated rotational speed. The maximum thrust is obtained when the torque or shaft power reaches the rated value.

For lower altitude and wind speed, the torque reaches the rated value first, while the rotational speed and the shaft power are lower than rated value. Therefore, a negative pitch angle ($\Delta \theta < 0$) is employed to increase the rotational speed and shaft power at the rated torque. The maximum thrust is obtained when the rotational speed or shaft power reaches the rated value.

5. Results and discussion

5.1. Design optimization of baseline propeller (fixed-pitch)

Take 2 meters and 2-bladed high-altitude propeller for example. The classic low Reynolds number airfoil E387 is used for each section. The design working condition is at the altitude of 25km, wind speed of 40m/s and rotational speed of 1200r/min. The optimization target is max thrust with restriction to the shaft power less than 1.0 kW. The optimization model is described as

$$\text{Maximize : } T_s$$

$$\text{s.t. } P_{s0} - P_s > 0$$

(5)
in which, $T_r$ is the thrust of the propeller. $P_s$ is the shaft power and the subscript “s0” means maximum shaft power. The optimized geometry is shown in Figure 6. Figure 7 demonstrates the pressure contours and streamlines of flow around the propeller at the section of 75%R.

**Figure 6.** Geometry of the baseline (fixed-pitch) propeller (25km, 40m/s).

**Figure 7.** Pressure contours and streamlines at 75%R (25km, 40m/s, 1200rpm)

5.2. Comparison of aerodynamic performance between fixed-pitch and variable-pitch propeller

At the altitude of 10km and wind speed of 10m/s, the aerodynamic performances of fixed-pitch propeller and variable-pitch propeller are calculated under the constraints of rated torque 8N.m, shaft power 1Kw and rotational speed 1200r/min. Figure 8 shows that the rotational speed and shaft power go up with the decrease of pitch angle. Due to the restriction of rated torque, the rotational speed and shaft power are unable to reach their rated value. Figure 9 shows that a peak of maximum thrust is located at a pitch angle of -19°. When the pitch angle is less than -19°, the maximum thrust decreases in spite that the shaft power is higher, for the reason of a negative effective attack angle and large flow separation.

**Figure 8.** Rotational speed and shaft power of variable-pitch propeller under the constraints of rated torque, shaft power and rotational speed.

**Figure 9.** Maximum thrusts of fixed-pitch propeller and variable-pitch propeller with different pitch angles.

Table 1 shows the comparison of aerodynamic performance between fixed-pitch and variable-pitch propeller, at different altitude and wind speed. With the constraint of rated torque, the rotational speed of variable-pitch propeller is significantly higher than that of fixed-pitch propeller. The lower the altitude, the greater the relative increase in rotational speed. Under the same torque constraints, the relative increase of shaft power is nearly the same as that of rotational speed. Particularly, the relative increase of rotational speed and shaft power can reach as much as 1.5 times for variable-pitch
propellers, under the ground conditions. Although the efficiency of variable-pitch propeller is lower than that of the fixed-pitch propeller, its maximum thrust is greatly increased for the reason the shaft power of the variable-pitch propeller is significantly higher than that of the fixed-pitch propeller. The maximum relative increment of the maximum thrust can reach more than 80%. In addition, the rotational speed and torque of the variable-pitch propeller are closer to their rated value of electric motor. Thus the matching of the variable-pitch propeller and the electric motor is better, resulting in a more efficient working condition of electric motor.

**Table 1.** Comparison of aerodynamic performance between fixed-pitch and variable-pitch propeller.

| Altitude (km) | Wind speed (m/s) | Pitch angle (°) | Rotational speed (r/min) | Torque (N.m) | Shaft power (kW) | Max.thrust (N) | Efficiency (%) |
|--------------|-----------------|----------------|--------------------------|-------------|-----------------|---------------|--------------|
| 20           | 25              | Fixed-pitch    | 0                        | 836         | 7.986           | 0.699         | 22.89        | 81.84        |
|              |                 | Variable-pitch | -9                       | 1200        | 7.915           | 0.995         | 31.24        | 78.52        |
|              |                 |                | Relative Δ %             | /           | +43.54          | /             | +42.35       | +36.47       | -4.06        |
| 15           | 15              | Fixed-pitch    | 0                        | 542         | 7.997           | 0.454         | 24.30        | 80.32        |
|              |                 | Variable-pitch | -17                      | 1150        | 7.995           | 0.963         | 42.54        | 66.28        |
|              |                 |                | Relative Δ %             | /           | +112.17         | /             | +112.11      | +75.06       | -17.48       |
| 10           | 10              | Fixed-pitch    | 0                        | 366         | 7.967           | 0.305         | 24.56        | 80.43        |
|              |                 | Variable-pitch | -19                      | 878         | 7.987           | 0.734         | 44.98        | 61.25        |
|              |                 |                | Relative Δ %             | /           | +139.89         | /             | +140.66      | +83.14       | -23.85       |
| 5            | 8               | Fixed-pitch    | 0                        | 278         | 7.961           | 0.232         | 23.95        | 86.68        |
|              |                 | Variable-pitch | -19                      | 671         | 7.973           | 0.560         | 42.98        | 61.38        |
|              |                 |                | Relative Δ %             | /           | +141.37         | /             | +141.38      | +79.46       | -29.19       |
| 0            | 6               | Fixed-pitch    | 0                        | 213         | 7.900           | 0.176         | 24.16        | 82.27        |
|              |                 | Variable-pitch | -20                      | 547         | 7.958           | 0.456         | 43.21        | 56.88        |
|              |                 |                | Relative Δ %             | /           | +156.81         | /             | +159.09      | +78.85       | -30.86       |

**6. Conclusions**

The aerodynamic performance of variable-pitch propellers for high-altitude UAVs are studied. The maximum thrust of fixed-pitch propeller is limited by the rated torque of electric motor at lower altitude, resulting in a poor matching of propeller and electric motor. Using variable-pitch propeller can obviously increase the rotational speed and shaft power under the constraint of rated torque, leading to a larger maximum thrust. The rotational speed and torque of the variable-pitch propeller are closer to their rated value of electric motor, resulting in a better matching of propeller and electric motor, and electric motor operates more efficient. Compared with fixed-pitch propeller, the maximum relative increment of the maximum thrust can reach more than 80% for variable-pitch propeller.

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