Modeling and Numerical Simulation of Stratospheric Aircraft Propulsion System

Xingjun Yuan¹*, Jiming Wang¹*, Xuan Tong¹ and Fengmei Wei²

1. Systems Engineering Research Institute, Beijing, 100094, China
2. CASIC Space Engineering Development Co., Ltd., Beijing, 100143, China

*E-mail: yuanxingjun123@163.com; 953186879@qq.com

Abstract. Aiming at propulsion system of stratospheric, a high altitude propeller was designed. Avoiding the singularity of equations in the iterative process, the interference angle equation was improved and the designed propeller was calculated by the strip theory. The three-dimensional Navier-Stokes equations were used to simulate the complex flow around the designed propeller and its aerodynamic characteristics were analyzed, in which the k-ω turbulence model was used. The accuracy of the numerical simulation was determined by the calculation of different grid numbers. The results show that the designed propeller can satisfy the requirement of propulsion system and the strip theory and numerical simulation can provide the reference for the design of stratospheric propeller.

Keywords: stratospheric; propulsion system; high altitude propeller; strip theory; numerical simulation

1. Introduction
In recent years, stratospheric aircrafts have received the great attention and many countries around the world have carried out some relevant researches. The stratospheric aircraft has important military applications, which flies between aeronautics and astronautics. Influenced by the high altitude environment, the propulsion system of the stratospheric aircraft has its unique composition.[1-2] Since the propeller is an important part of the propulsion system, it is necessary to study. The efficiency of the high altitude propeller directly affects the efficiency of the whole propulsion system, so the design and analysis of the high altitude propeller becomes the primary task of the stratospheric aircraft propulsion system.

At present, some scholars have done a lot of researches in designing and analyzing the high altitude propeller. L. Danielle Koch used the advanced ducted propfan analysis code (ADPAC) and numerical calculation to calculate the aerodynamic performance of the high altitude propeller.[3] Anthony Colozza had introduced in detail the design method of the high altitude propeller and proposed the consistent design method of the stratospheric propeller.[2] Wang Haojie had carried out the aerodynamic design of the propeller for the unmanned aerial vehicle using the blade theory and obtained good results.[4] Liu Yuanqiang used the strip theory to predict the propeller performance and verified the feasibility of the strip theory to calculate the high altitude propeller by the wind tunnel test.[5] Deng Zhiwei calculated the interference angle by the secant line method and established the propeller model by the strip theory.[6] Liu Peiqing used the numerical method to calculate the performance parameters of the high altitude propeller, compared with the wind tunnel test results, and
proved the feasibility of the numerical simulation to calculate the aerodynamic characteristics of the propeller.[7] Wang Yufu used the sliding grid method to calculate the high altitude propeller, compared with the wind tunnel test results, and proved the feasibility of the numerical simulation to calculate the complicated flow around the propeller.[8] In this paper, the high altitude propeller is designed by analyzing the requirements of the stratosphere aircraft propulsion system and the accuracy of the design propeller is verified by the strip theory and numerical simulation method. At the same time, the efficiency of the high altitude propeller is relatively high at the design point.

2. Strip theory of high altitude propeller

The blade theory of the propeller is mainly based on the vortex theory and Prandlt’s finite wings theory. The relationship between the blade geometry and aerodynamic force is established.[9]

If the number of propeller blades is \( N_B \) and the radius of propeller hub is \( r_0 \), the propeller thrust is

\[
T = \frac{1}{2} \rho V_o^2 N_B \int_{r_0}^{r} T \, dr
\]

The circumference force of the propeller is

\[
F = \frac{1}{2} \rho V_o^2 N_B \int_{r_0}^{r} Q_r \, dr
\]

The torque of the propeller is

\[
M = \frac{1}{2} \rho V_o^2 N_B \int_{r_0}^{r} Q \, dr
\]

The efficiency of the propeller is

\[
\eta = \frac{T V_0}{2 \pi n M} = \frac{V_0}{2 \pi n} \frac{\int_{r_0}^{r} T \, dr}{\int_{r_0}^{r} Q \, dr}
\]

When the aerodynamic characteristics of propeller are calculated, The known variables are as follows: the radius of the blade element \( r \), the chord of the blade element \( b \), the number of blade \( N_B \), the incidence angle \( \theta \), the lift coefficient \( C_L \), the drag coefficient \( C_D \).

The axial velocity interference factor is

\[
a = \frac{\tan \varphi [1 + \tan \varphi \tan (\varphi + \gamma)]}{\tan \varphi [1 + \tan \varphi \tan (\varphi + \gamma)] - 1}
\]

The circumference velocity interference factor is

\[
a' = a \tan \varphi \tan (\varphi + \gamma)
\]

The interference angle \( \beta \) is determined by the Newton iteration method.

\[
C_{t, \sigma} = \frac{4 \sin (\varphi_o + \beta) \tan \beta}{1 - \tan \gamma \tan \beta}
\]

\[
K = \frac{C_{t, \sigma} b (1 + a)^2}{\sin^2 \varphi \cos \gamma}
\]

\[
T_c = K \cos (\varphi + \gamma)
\]

\[
Q_c = K r \sin (\varphi + \gamma)
\]
The strip theory of the propeller is derived from the assumption that the number of the blade is infinite. Actually, the number of the blade is finite. Prandlt proposed the momentum loss factor to modify the strip theory.\[9\] The equation is as follows.

\[
2 \arccos f \frac{Fe}{\pi} = \frac{N_B}{2} \frac{R - r}{R \sin \phi_1}
\] (11)

In general, \(R \sin \phi_1\) of the equation (12) can be modified with \(R \sin \phi_0\) and the error can meet the requirements of the engineering precision. So the thrust and torque need multiply by the equation (11).

3. **Calculation on the high altitude propeller by the strip theory**

It is very important to ensure the interference angle, when using the strip theory to calculate the aerodynamic characteristics of the propeller. We can use the Newton iteration method and secant method to obtain the interference angle. The solution equation of the interference angle is as follows.

\[
f(\beta) = C_L \sigma - \frac{4 \sin(\phi_0 + \beta) \tan \beta}{1 - \tan \gamma \tan \beta} = 0
\] (13)

Changing the equation (13) to

\[
f(\beta) = \frac{C_L \sigma (1 - \tan \gamma \tan \beta) - 4 \sin(\phi_0 + \beta) \tan \beta}{1 - \tan \gamma \tan \beta} = 0
\] (14)

The equation (14) can be changed as

\[
F(\beta) = C_L \sigma (1 - \tan \gamma \tan \beta) - 4 \sin(\phi_0 + \beta) \tan \beta = 0
\] (15)

The lift coefficient \(C_L\) can be obtained by the XFOIL program or the Fluent software. The XFOIL program, developed by Mark Drela, is the turbulent transport model which is based on the surface element method, viscous boundary layer and the free boundary layer.\[10\] The angle of attack of the blade element changes constantly, so \(C_L\) and \(C_D\) also change. In this paper, XFOIL program and Fluent software are used to calculate the aerodynamic of S1223 airfoil. Then these data are called by the spline interpolation functions of Matlab software.

Fluent is used to calculate the aerodynamic characteristics on condition of the low Reynolds number, because the results of Fluent are more accurate. In this paper, we calculate the aerodynamic data on condition of \(Re=10000, 20000, 30000, 40000, 50000\) and \(\alpha=1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\). The resulting curves of the lift and drag coefficients are shown in Figure 1.

![Figure 1](image_url)

**Figure 1.** The lift and drag coefficients of S1223 airfoil

The lower \(Re\) is, the smaller the Angle of attack at the separation point of S1223 laminar flow is from figure 1. When \(Re\) is 40000, the Angle of attack (AOA) at the separation point is 11 degrees. When \(Re\) is 30000, AOA at the separation point is 10 degrees. When \(Re\) is 20000, AOA at the separation point is 8 degrees.
4. Numerical simulation of high altitude propeller

4.1. Calculation model
Fluent software is used to calculate the aerodynamic characteristics of high altitude propeller. The propeller data is selected from Reference [11]. CATIA software is used to establish the propeller solid model. Gambit software is used for meshing. The entire flow field area of the propeller is set as a large cylinder. The upstream length is 10 times diameters, the downstream is 20 times diameters, and the span is 10 times diameters. The flow field around the propeller is a small cylinder, which can be used as the encryption grid.

4.2. Calculation method
The pressure based solver is adopted to calculate the aerodynamic characteristics of the propeller in this paper. The governing equations are based on Reynolds mean Navier-Stokes equations. The governing equation is discretized by the finite volume method. The coupled pressure and velocity adopts the Coupled algorithm. The Shear Stress Transport k-ω turbulence model is used to calculate the propeller.

4.3. Boundary condition
The boundary conditions are the velocity inlet boundary and the pressure outlet boundary. The atmospheric pressure at 20km is 5474.9pa, the pressure outlet pressure is 0Pa, and the velocity is 20m/s. The rotating coordinate system is adopted in the flow field area. The propeller WALL is set as a stationary relative coordinate system, and the propeller rotates at a certain speed relative to the flow field. So the real flow field of the propeller can be simulated in the high altitude environment.

4.4. Calculation results
The comparison curves of the numerical calculation to the thrust coefficient, power coefficient and efficiency of the propeller, strip theory and wind tunnel experiment results are shown in Figure 2.

| λ     | T    | M    | C_T  | C_P  | η    |
|-------|------|------|------|------|------|
| 0.7385| 246.6| 266.5| 0.0904| 0.0945| 70.69|
| 0.6154| 480.3| 443.4| 0.1223| 0.1091| 68.96|
| 0.5275| 724  | 624.8| 0.1354| 0.1130| 63.23|
| 0.4615| 1017 | 826.3| 0.1457| 0.1144| 58.77|

Figure 2. thrust coefficient, power coefficient and efficiency curves

The thrust coefficients calculated by the numerical simulation and strip theory are basically consistent from Figure 2. The power coefficient calculated by the numerical simulation is larger than the strip theory and the wind tunnel experiment. The efficiency of the numerical simulation is more consistent with the experimental data. So the numerical simulation can be used to predict the performance of the high altitude propeller.

When the propeller speed is 20m/s, the aerodynamic characteristics of the high altitude propeller at different advance ratios are shown in Table 1.
5. Design of the high altitude propeller

The design parameters of the high altitude propeller mainly include the propeller speed $V_0$, the rotation speed $n_s$, diameter $D$, incidence angle $\theta$, chord $b$, section airfoil, and blade number $N_B$.

1. The tip Mach number of the propeller generally is less than 0.8. So the rotation speed of the propeller can be ensured.

$$Ma = \sqrt{\frac{V_0^2 + (\pi D n_s)^2}{c}} \leq 0.8$$  \hspace{1cm} (16)

2. There is a consistent relationship between the incidence angle $\theta$ and chord $b$ for the design of the high altitude propeller.

$$b = (0.084241 - 0.85789r + 4.7176r^2 - 9.6225r^3 + 8.5004r^4 - 2.7959r^5)d$$

$$\theta = \phi_{0.7} + 0.4387 + 0.3040r - 3.9616r^2 + 5.1180r^3 - 1.6284r^4 - 0.3244r^5$$  \hspace{1cm} (17)

3. Eppler387 and S1223 airfoils are both suitable for the section airfoil of the high altitude propeller. But the aerodynamic performance of S1223 at the low Re is better than Eppler387. So S1223 is selected to design the high altitude propeller.

According to the requirements of the stratosphere propulsion system, the design parameters of the propeller: $D=2.4\text{m}$, $V_0=28\text{m/s}$, $n_s=1000\text{rpm}$, $T=98\text{N}$, $R_r=0.1R$, $\theta_{0.7R}=20.5^\circ$.

6. Results of high altitude propeller

The propeller thrust and torque are calculated under different mesh numbers, when the rotation speed is 960rpm. The calculation results are shown in Figure 3.

![Figure 3. Aerodynamic data of propeller under different mesh numbers](image)

From Figure 3 different cells have influence on the propeller thrust and torque and the results tend to be stable with the increase of mesh. Considering the calculation time and cost, 152 million cells are used to calculate the high altitude propeller.

The aerodynamic characteristics of the high altitude propeller are obtained by the strip theory and numerical simulation under different advance ratios and the results are shown in Figure 4. From Figure 4 the errors of the strip theory and numerical simulation are less than 5%. The thrust coefficient, power coefficient and efficiency can satisfy the engineering precision. So the strip theory and numerical
simulation can be used to calculate the aerodynamic characteristics of the high altitude propeller. When $\lambda=0.7$, the thrust obtained by the CFD method is 98.7N, the torque is 44.8Nm, the efficiency is 63.1%. The design high altitude propeller can meet the requirement of the stratosphere propulsion system.

![Figure 4](image)

**Figure. 4** thrust coefficient, power coefficient and efficiency curves

7. Conclusions
In this paper the aerodynamic characteristics of the high altitude propeller are calculated by the numerical simulation method. The feasibility of the numerical calculation to the high altitude propeller is verified by comparison with the strip theory and the wind tunnel experiment data. Avoiding the singularity of equations in the iterative process, the interference angle equation was improved.

Aiming at the stratospheric propulsion system, a high altitude propeller is designed and the design high altitude propeller is calculated by the strip theory and numerical simulation method. The results show that the design propeller can satisfy the requirement of propulsion system and the strip theory and numerical simulation can provide the reference for the design of stratospheric propeller.

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