The study of spacing influence on the performance of Contra-Rotation-Propeller in stratospheric airship

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Abstract. According to the requirements of a foreign high-altitude airship project, the Single-Rotation-Propeller (SRP) was designed under the maximum endurance factor criterion. The spacing influence on the Contra-Rotation-Propeller (CRP) was studied by numerical simulation analysis, the performance of front and rear propeller was compared with SRP. The result indicated that CRP was more efficient than SPR, the CRP has enormous potential in enhancing the aerodynamic performance.

1. Introduction

The long-endurance, low-energy consumption, and high security make the stratospheric airship extensive application in both military and civilian fields. Efficiency propelling propeller is beneficial to improve the maneuverability and sustainability of airship, which cannot be matched by a turbojet or turbofan.

However, the environment at the stratosphere, which above 20 km, has a much smaller air density. Also, the advance velocity of stratospheric airship is 10 m/s which are extremely slow. The low Reynolds number and small advance ratio make it a big challenge to design an efficient propelling propeller. The Counter-Rotation-Propeller (CRP) is used to improve the efficiency.

The airfoil of high altitude vehicle was researched by prof. Michael S Selig [1], [2], the aerodynamic characteristics of six typical low Reynolds number, high lift, and low resistance airfoils were analyzed and wind tunnel experiments are carried out. Angleo[3] proposed a method by design the chord length and twist Angle to maximize propeller efficiency under design requirements, Xiang [4] improved the Angleo’s method to make it more content with the requirement of engineering application.

Many experimental investigations of CRP have been conducted during the last century, Biermann and Hartman [5] found that the performance of counter-rotating propellers was significantly improved at lower advance ratio. Naiman [6] developed a method for calculating the performance of a CRP from the section characteristics of the blade elements. Tang’s [7] research indicated the performance of CRP is different with variation of Reynolds number, and the efficiency of CRP achieved appears to be a few percent greater than that for a standard conventional propulsion system. Chen [9], Liu [10] and Wang [11] studied other aspects of CRP.

This paper designed a SRP which all airfoils along the radial direction of the propeller worked under the maximum endurance factor ($C_l^{1.5}/C_d$), the CRP was composed of two coaxial SRP, aerodynamics of was analyzed and compared with SRP.
2. The Performance of Single-Rotation-Propeller
According to the requirements of a foreign high-altitude airship project, the propeller design indexes were proposed as follows:

| Altitude | Velocity | Rated speed | Rated load | Diameter | Power |
|----------|----------|-------------|------------|----------|-------|
| 20 km    | 10 m/s   | 500 RPM     | ≥ 180 N    | ≤ 4 m    | ≤ 2500|

### 2.1. the design of SRP
The two-blade propeller was selected due to the low speed and large diameter of the SRP, the propeller-tips Mach number should be restricted as follows [1]:

\[
\frac{\sqrt{(\pi D n_s)^2 + V_0^2}}{a} \leq 0.7
\]

\[
D \leq \frac{\sqrt{(0.7a)^2 - V_0^2}}{\pi n_s} = 7.88 \text{ m} \tag{2}
\]

Where the D was the diameter of the SRP, \( n_s \) was the rotation speed per second, \( V_0 \) was the forward velocity, \( a \) was the local sound velocity which can be calculated by the local temperature. The diameter of SRP was chosen 4 m, due to the restriction of the design indexes. The hub of the propeller was chosen 25% of the diameter.

Prandtl simplified method was adopted to calculate the thrust distribution of the minimum energy dissipation and accordingly calculated the appropriate propeller chord length to minimize the energy loss of the propeller. The induction Angle of each section of the propeller was calculated, so that all airfoils along the radial direction of the propeller worked under the maximum endurance factor (\( C_{1.5} / C_d \)), made the propeller had the highest efficiency [12].

The shape parameters of the propeller were shown in Figure 1. Where the radial location was the location related to the radius, and the relative chord length was related to the diameter.

![Figure 1. The shape parameters of the propeller](image)

The 3D model of the SRP was constructed by the CAD software according to the design, which was shown in Figure 2.
2.2. Numberical simulation anlysis of Single-Rotation-Propeller

STAR-CCM+ was used for numerical simulation analysis of the SRP, the control equation was discretized by the finite volume method, the external flow field was separated by three-dimensional steady constant density, Reynolds average N-S equation and k-ω turbulence model was adopted.

### Table 2. The rated atmospheric conditions for numerical simulation

| T/K  | ρ/(kg/m³) | P/ Pa | a/(m/s) | μ/(kg/m·s) |
|------|-----------|-------|---------|------------|
| 216.7| 0.08805   | 5474.9| 295.07  | 1.4216 × 10⁻⁵ |

The performance of the SRP at different rotation speed was analyzed under the rated atmospheric condition which was shown in Table 2. As shown in Figure 3, the thrust, torque, and power were increased as the rotation speed increases, the efficiency increased a little firstly, reaching the peak 86.21% at 300 RPM, then decline gradually. The thrust and power at 500RPM were 98.98 N and 1298.71 W, which were satisfied the design indexes of the SRP.

![Figure 3. The performance of the SRP](image)

3. The Performance of Counter-Rotation-Propeller

The front propeller (FP) and rear propeller (RP) were components of the CRP, which were exactly the same except the rotational directions. The spacing of 0.8m, 1.2m, 1.6m, 2m, 2.4m were calculated at the rotation speed of 500RPM.

STAR-CCM+ was used for numerical simulation analysis of the CRP, which the control equation and turbulence model were consistent with the SRP.
As shown in Figure 4, the thrust of the front propeller was increased as the spacing increased, the rear propeller was climbed up first and then decline, the maximum thrust was occurred at the spacing of 1.6m. The total thrust tendency of CRP was consistent to the rear propeller, the total thrust beyond the two independent SRPs only at the spacing of 1.6m.

The differences between front propeller, rear propeller and SRP prove the existence of interference between front and rear propellers. The total thrust of CRP was mostly less than two independent SRPs, only in certain spacing had a higher total thrust, which the interference was disadvantage to the total thrust. The thrust of the front propeller was less than SRP, and the rear propeller was more, it indicated that the rear propeller was beneficial from the CRP while the front propeller was not conducive to.

The torque of front propeller and CRP were decreased as the spacing increased, which was shown in Figure 5, the rear propeller was decline firstly and then climb up. The torque of the front propeller and rear propeller were less than SRP, which made the total torque of CRP was less than two independent SRPs. The rear propeller impacted more from CRP which torque was less than front propeller.
Figure 6. The efficiency of the CRP compare to SRP

As shown in Figure 6, the efficiency of the front propeller was increased as the spacing increased, and the rear propeller and CRP were climbed up first and then decline. The efficiency of the front propeller increased more than the loss of the rear propeller, making the efficiency of CRP exceeded the SRP.

4. Conclusion

The thrust, torque, and power of SRP were increased as the rotation speed increases, the efficiency increased a little firstly then decline gradually. The thrust and power at 500RPM were satisfied the design indexes, which could be used to constitute the CRP.

The differences between front propeller, rear propeller and SRP prove the existence of interference between front and rear propellers, which was beneficial to rear propeller and not conducive to front propeller. The interference increased the thrust of the rear propeller and decreased the thrust of the front propeller, which reduced the torque and power of both, making the efficiency of the rear propeller exceed the SRP.

The thrust, torque, and power of CRP were less than two independent SPRs. The thrust reduction of CRP was not significant, but there was a certain drop in torque and power, which made the efficiency of CRP beyond the SPR.

The CRP has enormous potential in enhancing the aerodynamic performance, by optimizing the geometric parameters of the front and rear propeller, the thrust force can be effectively improved while improving the efficiency.

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