The study of rotate speed 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.

Research indicated the performance of counter-rotating propellers was significantly improved at lower advance ratio [1]. The Counter-Rotation-Propeller (CRP) is used to improve the efficiency [2]-[3], which the advance velocity of stratospheric airship is extremely slow.

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 [4]. The spacing influence on the performance of CRP was researched [5], but the researched of rotate speed influence was insufficient. Wang [6] and Xie [7] 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 (\(C_1^{1.5}/C_d\)), the CRP was composed of two coaxial SRP, aerodynamics of was analyzed and compared with SRP.
2. The Model of Propeller

According to the requirements of high-altitude airship project, the propeller design indexes were proposed as follows:

| Altitude | Velocity | Rated speed | Rated load | Diameter | Power |
|----------|----------|-------------|------------|----------|-------|
| 20 km    | 15 m/s   | 500 RPM     | ≥ 200 N    | ≤ 4 m    | ≤ 5000|

The propeller was designed under the maximum endurance factor \( C_{\varepsilon} \), made the propeller had the highest efficiency [8]. 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.

The 3D model of the SRP was constructed by the CAD software according to the design, which was shown in Figure 2.

3. The Performance of the Propeller

3.1. The Performance of SRP

The performance of the SRP at different rotation speed was analyzed under the rated atmospheric condition. 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 72.22% at 350 RPM, then decline gradually. The thrust and power at 500RPM were 102.37 N and 2361.95 W, which were satisfied the design indexes of the SRP.
3.2. The spacing influence on CRP

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, 2.8m were calculated at the rotation speed of 500RPM.

The performance of the CRP in different spacing was given in the Figure 4. The thrust of FP was consistently lower than SPR at all spacing and increases with increasing spacing. The thrust of RP was consistently higher than SPR at all spacing and decreases with increasing spacing, making the total thrust of CRP was increased firstly and then kept the same. When the spacing was greater than 2m, the total thrust was slightly higher than 2-SPP which was two independent SRPs. The efficiency of FP was increased as the spacing increased, and the RP and the CRP were climbed up first and then decline. The RP enhanced the efficiency more than the FP reduced, which make the efficiency of CRP exceeded SRP, and the efficiency was highest with the spacing of 2m.

According to the results of previous section, the spacing of 2m was chosen to research the rotate speed influence on CRP, which the rotate speed was given in Table 2.
### Table 2. The rotate speed of CRP

| No | Front Propeller/RPM | Rear Propeller/RPM |
|----|---------------------|--------------------|
| 1  | 250                 | 500                |
| 2  | 300                 |                    |
| 3  | 350                 |                    |
| 4  | 400                 |                    |
| 5  | 450                 |                    |
| 6  | 500                 |                    |
| 7  | 550                 |                    |
| 8  | 600                 |                    |

3.3. *The FP rotate speed influence on CRP*

As shown in Figure 5, the thrust of RP was descended as FP rotate speed increased, but the reduction is relatively small, made CRP thrust increased. The power variation trend was consistent with the thrust, the thrust and power was less than SRP when the FP rotate speed faster than 500 RPM.

![Figure 5. The performance of the CRP in different FP rotate speed](image1.png)

The efficiency of the CPR was given in Figure 6, the RP efficiency was descended while the FP was ascended as the FP rotate speed increased. But the CRP efficiency was decreased firstly and then increased. When the FP in a low RPM, the thrust and power was comparatively small, the RP efficiency played dominant roles, which made the CRP efficiency higher than the SRP. As the rotate speed increased, the FP thrust and power grew fast and began to affect the CRP, making the efficiency lower than the SRP. The FP efficiency was ascending which the growth rate was gradually slowing down. The RP efficiency was descending at the same rate, which began to lower than SRP when the FP was higher than 500 RPM.

![Figure 6. The efficiency of the CRP in different FP rotate speed](image2.png)
3.4. The RP rotate speed influence on CRP
As shown in Figure 7, the thrust of RP was ascend while FP was descended very slightly as RP rotate speed increased, making the increase trend of CRP was consistent with that of RP. The power variation trend was similar with the thrust, the thrust and power of FP was less than SRP at all rotate speed ranges.

![Figure 7. The performance of the CRP in different RP rotate speed](image)

The efficiency of the CPR was given in Figure 8, the FP efficiency was descended while the RP and CRP were ascended as the RP rotate speed increased. The RP efficiency was ascending which the growth rate was gradually slowing down, and both RP and CRP exceeded the SRP in about 470 RPM. The FP efficiency was descending which the decline rate was gradually slowing down, which began to lower than SRP when the RP was higher than 400 RPM.

![Figure 8. The efficiency of the CRP in different RP rotate speed](image)

4. Conclusion
The thrust, torque, and power of SRP were increased as the rotation speed increased, the efficiency increased firstly then decline gradually. The thrust and power at 500RPM were satisfied the design indexes.

The performance among FP, RP and SRP proved the existence of interference between front and rear propellers, which was beneficial to RP and not conducive to FP. The interference increased the thrust of the RP and decreased the thrust of the FP, making the thrust was slightly high than two independent
SPRs. The power of CRP was lower than the two independent SPRs, which made the efficiency of CRP beyond the SPR.

The spacing of 2m was selected to research the rotate speed influence on CRP, which the efficiency was highest among all the spacing. The RP efficiency was descend while the FP was ascended as the FP rotate speed increased. But the CRP efficiency was decreased firstly and then increased. The FP had an effect on the improvement of RP performance, and only at a high rotate speed would decline the performance. The FP efficiency was descended while the RP and CRP were ascended as the RP rotate speed increased. The RP has an impact on FP performance degradation, which is inconspicuous in low rotate speed.

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