Mechanical and Aerospace Engineering
B. Guan (Ed.)

doi:10.3233/ATDE250023

Research on the Influence of Design Variables on High Altitude Contra-Rotating Propeller Aerodynamic Performance

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Abstract. High altitude contra-rotating propellers are increasingly being utilized in High Altitude Long Endurance (HALE) aircraft, due to the significant improvement in aerodynamic efficiency of contra-rotating propellers compared to conventional propellers. This study compares the accuracy of the Multiple Reference Frame (MRF) quasi-steady calculation method with the unsteady calculation method, and employs the MRF quasi-steady method to analysis the effects of axial distance, twist angle, and the rotational speed ratio on the performance of contra-rotating propellers at high altitudes. The results indicate that within the studied range, an increase in axial distance leads to a slight improvement in the efficiency of the contra-rotating propellers, although the overall enhancement is minimal. Additionally, minor variations in the twist angle of the front and rear propellers are advantageous for enhancing the aerodynamic efficiency of the contra-rotating propellers. The maximum efficiency of the contra-rotating propellers is achieved when the rotational speed ratio is 1.05.

Keywords. Contra-rotating propeller, high altitude, aerodynamic performance, design variables

1. Introduction

For many years, stratospheric airships have been the focal areas of HALE aircraft. This aircraft has outstanding advantages, including extended flight endurance, higher operating altitudes, and broader coverage areas [1,2]. Given the long-endurance and solar energy utilization requirements of HALE aircraft, the propeller remains the primary choice for the propulsion system [3,4]. However, in the near space environment, where air density is low and kinematic viscosity is high, the aerodynamic efficiency of the propeller can be further improved through unconventional propeller layout designs.

Contra-rotating propellers refer to a configuration where two conventional propellers are mounted on two concentric shafts, and the two blades rotate in opposite directions to form a combined propeller system [5,6]. The primary principle is that the

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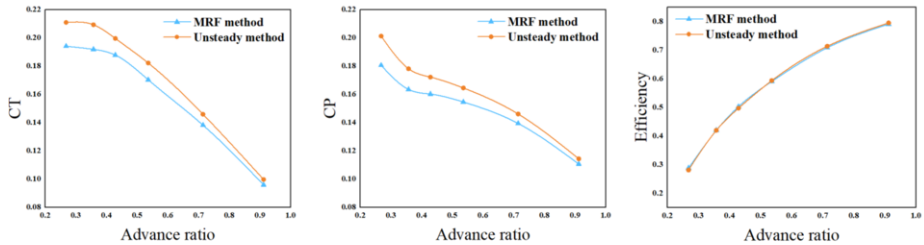
rear propeller can absorb the wake vortex energy loss induced by the front propeller, thereby effectively enhancing aerodynamic efficiency. Since the contra-rotating propeller system consists of two sets of propellers, there are more factors that influence the aerodynamic performance of the contra-rotating propellers. Hou et al. [7] utilized vortex theory to design the front and rear propellers separately, and the results indicate that this method increased the efficiency of the contra-rotating propeller by 10.24% compared to a single propeller. Zhang et al. [8] utilized numerical simulation to investigate the impact of blade number on the aerodynamic characteristics of contra-rotating propellers. The results indicated that the overall thrust of the contra-rotating propeller system increases with the number of blades. However, when the number of blades on the rear rotor is equal to that on the front rotor, further increasing the number of blades on the rear rotor results in a decrease in propulsive efficiency. Feng et al. [9] used numerical simulations to examine the impact of axial distance on the aerodynamic performance of contra-rotating propellers. The results showed that as the axial distance between the propeller shafts increased, the overall performance of the contra-rotating propellers showed minimal change. However, the efficiency improved slightly compared to the configuration with the minimum axial distance.

However, it is worth noting that current research on the influence mechanisms of contra-rotating propellers is largely conducted under low-altitude conditions, with relatively fewer studies focusing on those in the near space environment. To reduce the design variables for near space propellers, this paper compares the accuracy of the Multiple Reference Frame (MRF) quasi-steady numerical simulation method with that of the unsteady numerical simulation method. To conserve computational resources, the MRF quasi-steady simulation method is employed to analysis the influence of axial distance, twist angles of the front and rear propellers, and the rotational speeds of the front and rear propellers under different advance ratios for near space contra-rotating propellers. This study aims to provide a reference for the optimization design of near-space contra-rotating propellers.

2. Methods

In this paper, a multi-block structured grid is used to divide the spatial flow field around the propeller. The entire computational domain is divided into a stationary domain and a rotating domain. In order to simulate the rotation of the propeller, the Multiple Reference Frame (MRF) method is employed, eliminating the need for transient calculations. The inlet domain is defined with a speed far-field boundary condition, the outlet domain with a pressure far-field boundary condition, and the far domain with a pressure far-field boundary condition. The pressure and temperature values are set according to the real altitude. The blade surface is defined as a stationary, no-slip wall in relation to the adjacent zone.

The following figure compares the computed results for thrust coefficient (CT), power coefficient (CP), and efficiency between the MRF method and the unsteady method at different advance ratios. As shown, although there are some discrepancies between the MRF and unsteady methods in terms of CT and CP, their trends are entirely consistent, and the efficiency discrepancy is minimal. Therefore, to conserve computational resources while ensuring result reliability, the use of the MRF method for analysing the aerodynamic performance trends of near-space contra-rotating propellers is fully justified.



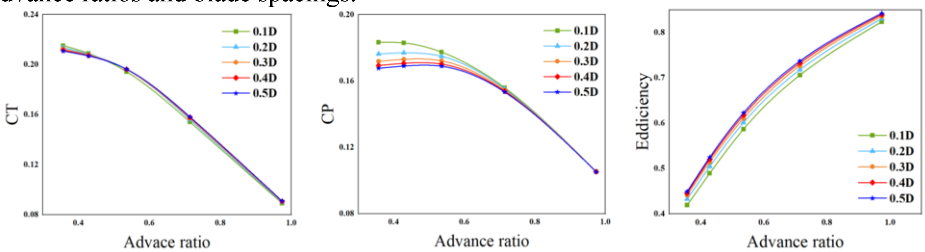
(a) CT (b) CP (c) Efficiency

Figure 1. Comparison of computational results between different methods.

3. Results and Discussion

3.1. Axial Distance

The axial distance between the front and rear propellers of a contra-rotating propeller in the near-space environment significantly influences the aerodynamic interference between the propellers, thereby affecting their aerodynamic performance. In the calculations, the front and rear propellers have the same propeller twist angle, and the contra-rotating propeller configuration is 2×2. The axial distance is varied and expressed as a proportion of the rotor disk diameter, with ratios of 0.10, 0.20, 0.30, 0.40, and 0.50 considered. The figure below illustrates the aerodynamic performance of the contra-rotating propeller at an altitude of 20 km and a wind speed of 20 m/s, examining different advance ratios and blade spacings.



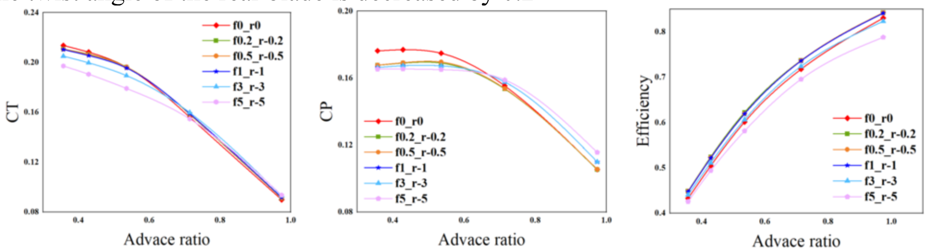
(a) CT (b) CP (c) Efficiency

Figure 2. The influence of axial distance on the aerodynamic performance of contra-rotating.

From the Figure 2, it can be observed that at low advance ratio, reducing the axial distance results in a slight increase in the total thrust coefficient. Conversely, at high advance ratios, increasing the axial distance also leads to a slight increase in the total thrust coefficient. However, overall, the total thrust coefficients of the contra-rotating propeller show minimal variation across different advance ratios and axial distances. Regarding the power coefficient, at low advance ratios, the effect of axial distance on the power coefficient is significant. Smaller axial distance results in a higher power coefficient for the contra-rotating propeller. When the advance ratio exceeds 0.8, the impact of axial distance on the power coefficient becomes negligible. In terms of efficiency, when the axial distance is within the range of 0.1D to 0.5D, the efficiency of the contra-rotating propeller improves with increasing axial distance across different advance ratios. However, when the axial distance exceeds 0.2D, the improvement in efficiency becomes less pronounced.

3.2. Twist Angle

In analysing the influence of twist angle on the aerodynamic performance of contra-rotating propellers, calculations were conducted for different advance ratios under the condition of simultaneous but opposite adjustments of the twist angles of the front and rear blades. The inter-blade spacing for both the front and rear blades was set to 0.2D, and the contra-rotating propeller was configured in 2×2 arrangement. The figure below illustrates the aerodynamic performance of the contra-rotating propellers at an altitude of 20 km and a wind speed of 20 m/s under various advance ratios and twist angles. The notation f0.2_r-0.2 indicates an increase of 0.2° in the twist angle of the front blade while the twist angle of the rear blade is decreased by 0.2°

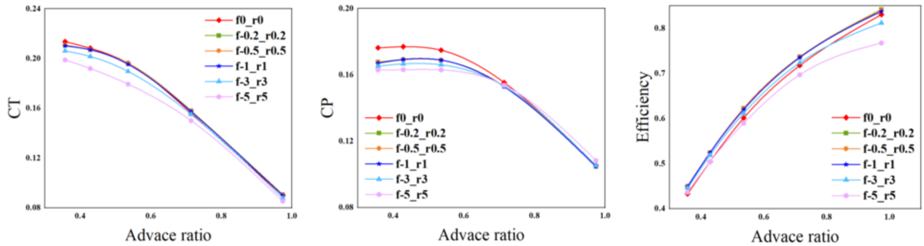


(a) CT (b) CP (c) Efficiency

Figure 3. The influence of increasing the twist angle of the front blade and decreasing the twist angle

Figure 3 shows that increasing the twist angle of the front blade while decreasing that of the rear blade has minimal impact on the thrust coefficient of contra-rotating propellers at low advance ratios (less than0.7). Specifically, a slight increase (less than or equal to1°) in the front blade's twist angle results in negligible changes to the thrust coefficient. Conversely, a significant increase (greater than or equal to1°) in the twist angle of the front blade, alongside a decrease in the rear blade's twist angle, results in a marked reduction in the thrust coefficient. For high advance ratios (greater than0.7), the variation in the thrust coefficient with respect to twist angle changes is not pronounced. Regarding the power coefficient, when the advance ratio is less than0.7, increasing the twist angle of the contra-rotating propeller leads to a gradual decrease in the power coefficient. In contrast, when the advance ratio exceeds0.7, the power coefficient gradually increases with an increasing twist angle. As for efficiency, when the twist angle changes slightly (less than3°), the efficiency improves compared to the baseline contra-rotating propeller, and the improvement is particularly noticeable for smaller changes (0.2° and0.5°). However, when the twist angle changes by5°, the efficiency of the contra-rotating propeller declines significantly.

The figure below illustrates the aerodynamic performance changes of the contra-rotating propeller when the twist angle of the front blade is decreased while the corresponding angle of the rear blade is increased. It is evident from the analysis that similar trends are observed regarding the thrust coefficient, power coefficient, and efficiency, particularly under low advance ratios where slight adjustments in twist angle have varying effects, and the efficiency reflects consistent behavior analogous to that observed when increasing the front blade's twist angle while decreasing that of the rear blade.



(a) CT (b) CP (c) Efficiency

Figure 4. The influence of decreasing the twist angle of the front blade and increasing the twist angle of the rear blade on the aerodynamic performance of contra-rotating propellers.

3.3. Rotational Speed Ratio

In analysing the effects of front and rear blade rotational speeds on the aerodynamic performance of the contra-rotating propeller, a method was employed where the rotational speeds of the front and rear blades changed simultaneously in opposite directions. Calculations were performed for the contra-rotating propeller under different advance ratios. In this analysis, the axial distance between the front and rear rows was set at 0.2D, and the twist angles for both the front and rear blades were kept identical. The contra-rotating propeller was configured as 2×2 setup, with benchmark rotational speeds of 220 rpm for both the front and rear blades. The speed ratio of the blades is defined as the front propeller rotational speed divided by the rear propeller rotational speed. The Table below presents the various rotational speed ratios.

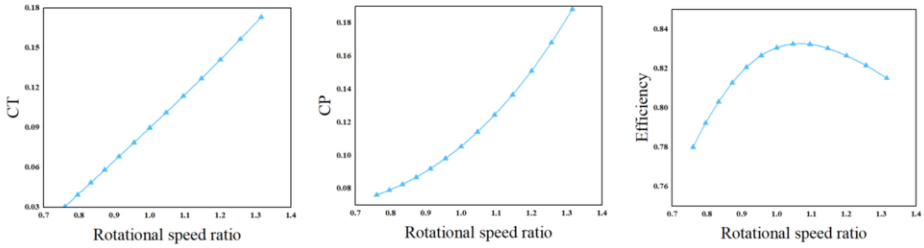
Table 1. Calculation conditions for decreasing front propeller rotational speed and increasing rear propeller rotational speed.

Calculation conditions	Altitude (km)	Wind speed (m/s)	Front blade rotational speed (rpm)	Rear blade rotational speed (rpm)	Speed ratio
1	20	20	215	225	0.956
2	20	20	210	230	0.913
3	20	20	205	235	0.872
4	20	20	200	240	0.833
5	20	20	195	245	0.796
6	20	20	190	250	0.760

Table 2. Calculation conditions for increasing front propeller rotational speed and decreasing rear propeller rotational speed.

Calculation conditions	Altitude (km)	Wind speed (m/s)	Front blade rotational speed (rpm)	Rear blade rotational speed (rpm)	Speed ratio
1	20	20	225	215	1.047
2	20	20	230	210	1.095
3	20	20	235	205	1.146
4	20	20	240	200	1.200
5	20	20	245	195	1.256
6	20	20	250	190	1.316

The figure below illustrates the aerodynamic performance of the contra-rotating propeller at an altitude of 20 km and a wind speed of 20 m/s for various front and rear propeller rotational speed ratio.



(a) CT (b) CP (c) Efficiency

Figure 5. Comparison of aerodynamic performance of the contra-rotating propeller at different rotational speed ratio.

From the Figure 5, it can be observed that the thrust coefficient and power coefficient of the contra-rotating propeller increase with the increase in the front and rear propeller rotational speed ratio. However, there exists an optimal front and rear blade speed ratio for efficiency, at which the contra-rotating propeller achieves maximum efficiency. The optimal rotational speed ratio is 1.05.

4. Conclusions

This study employs the MRF quasi-steady method to investigate the aerodynamic performance of contra-rotating propellers in near-space conditions, exploring the effects of various design variables on the aerodynamic characteristics of the contra-rotating propellers. The following conclusions are drawn:

1. As the axial distance increases, the efficiency of the contra-rotating propellers shows a slight improvement, while the thrust coefficient remains basically unchanged. In the case of a small advance ratio, the power coefficient decreases as the axial distance increases. However, at a large advance ratio, the variation in power coefficient remains relatively insignificant with changes in axial distance.

2. When the twist angles of the contra-rotating propellers are simultaneously varied by small angles in the opposite direction, the efficiency of the contra-rotating propellers can be enhanced while maintaining a relatively constant thrust coefficient. However, when the twist angles are varied by larger angles, a reduction in the efficiency of the contra-rotating propellers is observed.

3. The thrust coefficient and power coefficient of the contra-rotating propellers increase with an increasing rotational speed ratio. The maximum efficiency of the contra-rotating propellers is achieved when the speed ratio is 1.05.

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