Wind Tunnel Tests of the Counter-Rotating Propeller of Stratospheric Airship

Peiqing Liu[1, a], Jingwei Sun[2,b] and Zhihao Tang[3,c]

School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

[a]charmingwei0703@gmail.com, [b]lpq@buaa.com, [c]sunjingwei59@sina.com

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Abstract：*In this paper, a design of counter-rotating propeller (CRP) for stratospheric airship in low Reynolds number is tested in experiment for the first time. In consideration of stratosphere environment, a two-bladed counter-rotating propeller is designed for stratospheric airship. With the similarity theory of Reynolds number and advanced ratio, the experiment is conducted in low Reynolds number wind tunnel at Beihang University. The results indicate that counter-rotating propeller were 4%-7% percent more efficient than single-rotating propeller (SRP). This shows that for the counter-rotating propeller: 1) with the same diameter and power, the thrust coefficient is higher; 2) with the same thrust coefficient and power coefficient, the diameter could be reduced; 3) with the same thrust coefficient and diameter, the power coefficient could be reduced.*

Introduction

Stratospheric airship is now received more and more attention. Stratospheric airship need to meet the requirements of long-endurance. So there are many methods are adopted: 1) improve the ability of energy storage; 2) use the lighter materials; 3) improve the airship aerodynamic configuration [1] [2]. As a fact, the propeller for stratospheric airship has low efficiency than the propeller for high speed aircraft. Due to the stratosphere atmospheric density is small, Reynolds number of stratosphere is an order of magnitude smaller than the ground. The propeller propulsion for the stratosphere airship has low efficiency[3] [4]. Some existing methods to raise the capacity of the propeller propulsion: At first, can by changing propeller diameter, but due to the stratosphere critical Mach number is small, blade tip is easy to produces shock resistance, bigger blades bring great difficulty to install; Secondly, increase the number of the propeller can effectively improve the overall thrust, but too much consider the layout and balance the propeller torque, installation also has a lot of difficulties; At last, the counter-rotating propeller (CRP) offers the potential of a higher efficiency, smaller diameter along with a reduction of reaction torque when compared with a single rotation propeller (SRP) for equal input horsepower. This is due to the recovery of swirl energy by the rear rotor and the partial cancellation of moments since they are in opposite directions on the front and the rear rotors although not equal in magnitude[5].

Biermann and Gray took a wind tunnel experiment for counter-rotating propeller with high Reynolds number, verified that counter-rotating propeller can significantly improve efficiency[6] [7]. Biermann and Hartman took an experiments prove that counter-rotating propeller propulsion system for the overall efficiency significantly increase applies to lower advance ratio[8] [9]. Airship propeller propulsion works at a low advance ratio. As the energy increasingly nervous today, counter-rotating propeller propulsion applied to stratosphere airship has a good prospect.

Similarity Theory

Stratospheric air density is much smaller than the ground. How to simulation the low Re number environment on the ground must be studied first before taking the wind tunnel test. In this experiment, in order to ensure the movement similar and dynamic similar the advance ratio and Reynolds number similar conditions must be satisfied[10].

Advance ratio similarity determines the propeller working state movement is similar. The ratio of wind speed and the blade tip rotation speed is called advanced ratio.

$$\frac{V_{01}}{D_1 n_{s1}} = \frac{V_{02}}{D_2 n_{s2}} \qquad (2.1)$$

Dynamic similarity requires that various forces acting on the fluid particle is proportional to the size and in the same direction. In general, the fluid particle by forces include: unsteady inertia force, viscous force, gravity, elastic force. Ma number is the ratio of elastic force and inertial force, and it is also the ratio of air velocity and speed of sound. The Ma number similar conditions are the same to the advanced ratio similarity. For air, the gravity can be neglected. As a result, the Re number similarity become the most important condition. Re number is the ratio of inertia force and viscous force.

$$R_e = \frac{W_1 D_1}{\nu_1} = \frac{W_2 D_2}{\nu_2} \qquad (2.2)$$

W is the resultant velocity of the propeller blade element, ν is the dynamic viscosity coefficient(20 km altitude: ν =16.1×10-5m2/s, on the ground: ν =1.46×10-5m2/s). As the resultant velocity W is related to the blade tip speed, the formula (2.2) can be written as:

$$n_{s1} D_1^2 / \nu_1 = n_{s2} D_2^2 / \nu_2 \qquad (2.3)$$

Wind tunnel device

In this simulation, the propeller model is similar geometrical properties as those in reference [11] because of the lack of the appropriate data for low Re number CRP. The geometrical properties of this propeller were basically to achieve the highest single rotating propeller (SRP) efficiency and therefore it is not optimal for CRP[5]. Propeller diameter is 0.75m, SRP is two blade, CRP is 2×2. Low Reynolds number and high lift S1223 airfoils was chosen as the blade element.CRP 2×2propeller is shown in figure 1

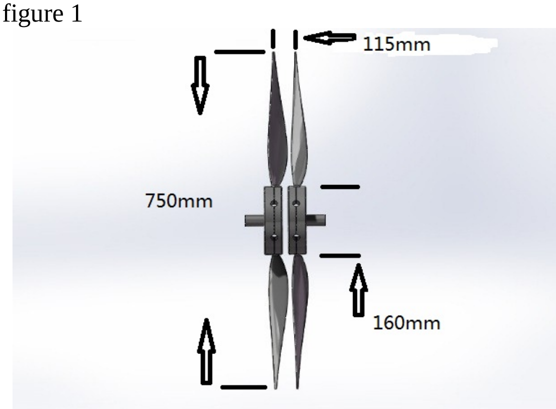

Figure. 1 counter-rotating propeller

This experiment was taken in low Reynolds number wind tunnel of buaa, as it is shown in figure 3.1. Experimental section diameter is 1.0m, the wind speed V0=0~20m/s, turbulence: k=1%, contraction ratio η =1.44.

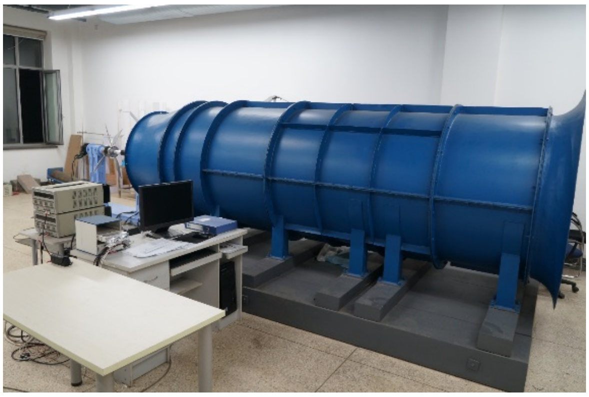

Figure. 2 low Reynolds number wind tunnel

The motor speed and data collection were controlled by the “CRP experiment system” operated under the LabView. Servo motor is used to control the revolving speed of the propeller. Strain gauge balance is installed on the propeller shaft to measure the force and moment. The result of a measurement is the averaging of 20 real-time signal value collected in the 4 seconds sampling period.

Experimental condition is shown on the chart1:space between two rotor is 150mm, setting angle of blade is 28.3° ,two rotors used the same speed.

Chart. 1 experimental condition

Wind speed (m/s)	Rotate speed (rpm)	Time interval (rpm)
0	400~1500	50
5	400~1500	25
7.5	400~1500	25
10	700~1500	25
12.5	700~1500	25
15	1000~1500	25
17.5	1000~1500	25

Error analysis

In this experiment, the force and torque was seven times repeated collection. As for multi-point measurement, each measuring point has the same repetitions and has the same accuracy. The formula for the uncertainly of multipoint measuring is shown in formula 4.1[12] [13]:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k}\sum_{j=1}^{n}(a_{ij}-\bar{a}_i)^2}{k(n-1)}} \qquad (4.1)$$

The random uncertainty of the measurement is shown in formula 4.2:

$$\Delta = t_\alpha \cdot \sigma \qquad (4.2)$$

{i} is the number of measuring points;

{n} is number of measurement of each measuring point;

{k} is total number of points;

{t_α}is confidence interval, determined by measuring frequency and confidence probability.

The repetitions is 7,

k=1,

n=7,

confidence probability is 0.95. $t_\alpha = 2.447$.

The uncertainty of each u（M）and u（T）can be calculated.

Error transfer formula is shown in 4.3:

$$\Delta\eta = \sqrt{\left[\Delta T\frac{\partial(\eta)}{\partial(T)}\right]^2 + \left[\Delta n_s\frac{\partial(\eta)}{\partial(n_s)}\right]^2 + \left[\Delta V_0\frac{\partial(\eta)}{\partial(V_0)}\right]^2 + \left[\Delta M\frac{\partial(\eta)}{\partial(M)}\right]^2} \qquad (4.3)$$

Field Code Changed

In this experiment, the flow velocity error and rotate speed error is under 0.5%. The efficiency error distribution of each measuring point is shown in figure 3:

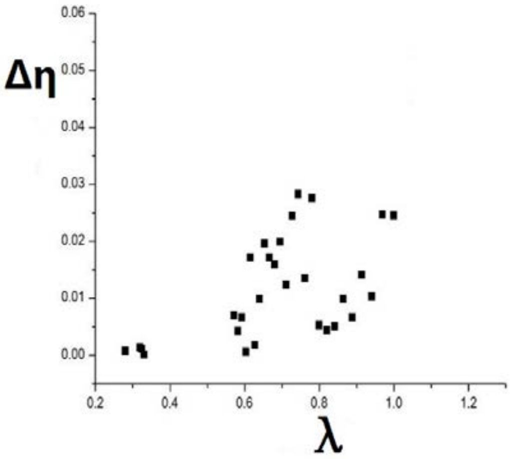

Figure. 3 propeller efficiency error distribution

Because the measurement of the force and torque has a fixed deviation, when the wind speed and rotate speed are low, the measurement precision is low. So the speed of measurement point is improved to improve the measurement accuracy. The higher rotate speed means better measurement accuracy. The maximum error is under 5%, and when it related to the low advance ratio region the maximum error is under 3%. The experiment is in a credible range error.

Results analysis

Reynolds number can be determined by control the rotating speed of propeller and the speed of wind tunnel. After measured the aerodynamic force of SRP, front propeller and rear propeller, the dimensionless aerodynamic parameters could be determined. By definition, these parameter is as follows:

（1）thrust coefficient of the propeller

$$C_t = \frac{t}{\rho {n_s}^2 D^4} \qquad (1)$$

The t is the pull.

（2）power of the propeller

$$C_p = \frac{P}{\rho n_s^3 D^5} \qquad (2)$$

Power coefficient is power coefficient, p is the power.

（3）efficiency of the propeller

$$\eta = \frac{tV_0}{P} = \frac{C_t}{C_P}\lambda \qquad (3)$$

With the advanced ratio is determined from 0.6-1.0, the thrust coefficient could be raised by improve the wind speed of wind tunnel as it shown in figure 4.

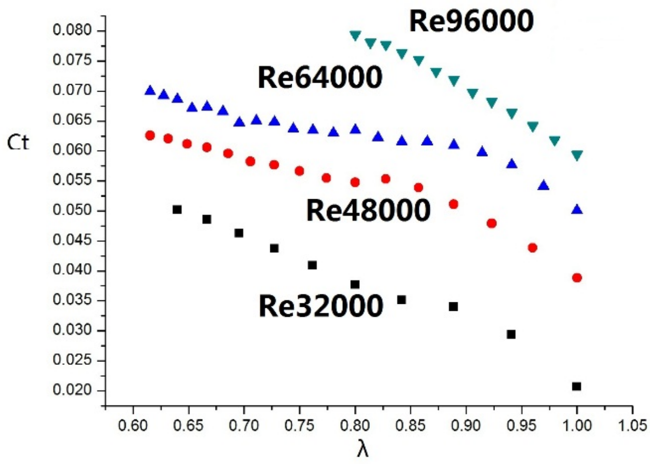

Figure. 4 Thrust coefficient with different wind speed

In general, as the Reynolds number increases, the thrust coefficient is improving. As the installation angle of propeller is fixed, the attack angle of the blade is determined by installation angle and advanced ratio. With the same advanced ratio, improve the wind speed, screw speed increase too. As it shown in figure 5, the efficiency could be increased by improving the Reynolds number. When Reynolds number is large, the efficiency curve is very near. The propeller's maximum efficiency is 72% when the advanced ratio is 0.8-1.0 and wind speed is 15m/s.

Chart. 2 the propeller efficiency

Wind speed/Re	λ： 0.8	0.88	0.91
5（32000）	40.6%	42.4%	31.3%
7.5（48000）	61.8%	63.0%	55.7%
10（64000）	61.8%	64.3%	61.6%
12.5（80000）	71.3%	64.6%	62.7%
15（96000）	72.4%	72.6%	70.0%

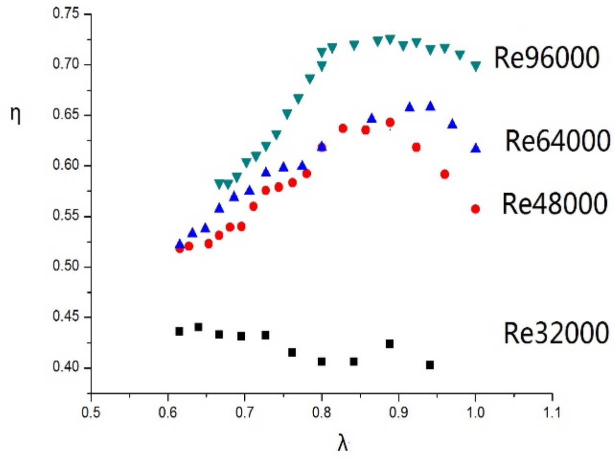

Figure. 5 η with different wind speed

The efficiency of the rear propeller is significantly higher than SRP. At the same condition, the efficiency of the front propeller is lower than SRP. As the advanced ratio is 0.5-1.1, the CRP could improve the efficiency by 4%-6% in contrast with the SRP as it shown in figure 6.

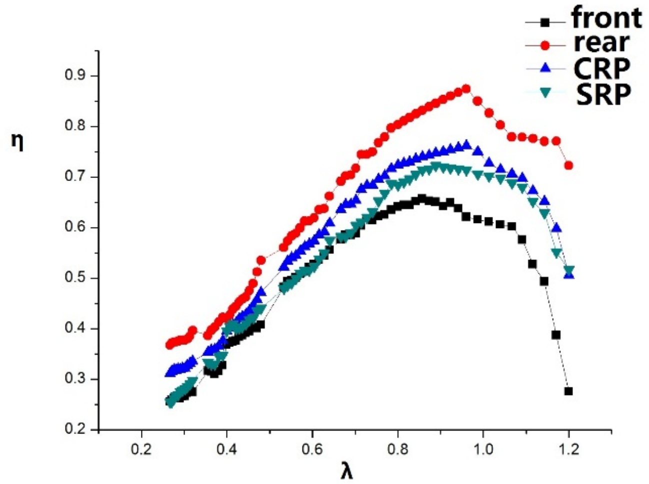

Figure. 6 η with different wind speed

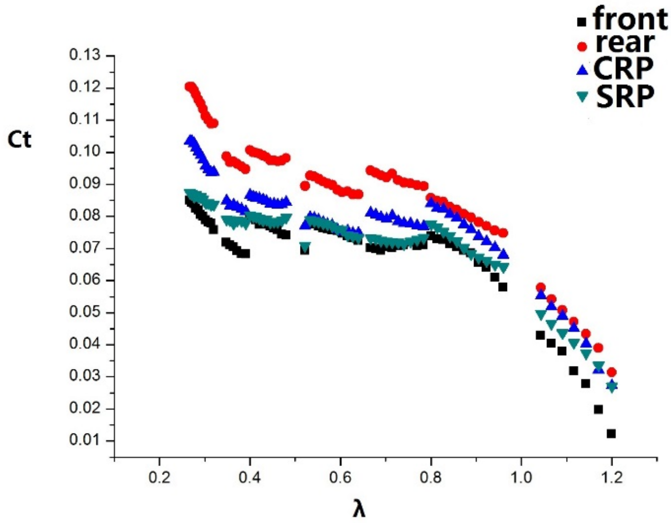

Figure. 7 Ct with different wind speed

In spite of the front propeller have the lowest thrust coefficient, the CRP has a higher thrust coefficient than SRP. The results indicate that the rear propeller have the highest thrust coefficient as it shown in figure 7.

Summary

In contrast with SRP, the wind test show that CRP for stratospheric ship could improve the efficiency by 4%-7%. This result could be used to guide the design of stratospheric airship propulsion system.

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