THE INVESTIGATION OF CYCLOGYRO DESIGN AND THE PERFORMANCE

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Abstract

The investigation over several possible coclogyo designs was performed in the paper. The concept of cyclogyro has existed almost 100 years, but still more research are needed. The effects of taper ratio, aspect ratio and winglets are investigated in this paper. The comparison between different designs shows that the tapered blades with larger aspect ratio can improve propellers performance. A new and simple blade structure is also presented to demonstrate how to keep blades with large aspect ratio work safely with neglectable weight penalty.

1 Introduction

The cyclogyro is a type of airplane equipped with cycloidal propellers. The cycloidal propeller is composed of two to more blades that rotates around an axis parallel to the blade (Fig. 1). When the aircraft hovers, the blades travels along a circle and when the aircraft moves backward or forward, the blades travels along a cycloid. The pitch angles of the blades are controlled by an eccentric mechanism. By setting the offset of the eccentric, the desired amplitude of the aerodynamic forces can be obtained. By varying the phase angle of the eccentric, the direction of the total force vector can be varied from 0 to 360 deg. The primary advantage of the cycloidal propeller is that it provides 360deg of vector thrusting at ease and this provides the airplane very good maneuverability. Since all sections of the blade on cycloidal propellers travel at the same speed, there is no strong tip vortex that will cause vibration and noise. Thus the cyclogyroes can be quieter than the helicopters. A possible configurtation of cyclogyro is shown in Fig. 1. A tail rotor is installed to balance the torque caused by main rotor. As shown in Fig. 2, the tail rotor in this case also generated lift which unloads the main rotor and save power. This is also superior to helicopters since helicopters waste power to balance the main rotor torque. The major disadvantage of the cycloidal propeller is that it is much heavier than screw propellers since big strut was needed to support the blades and the blades have to sustain large centrifugal force normal the to blade surface. The modern composite materials and innovative structural design can alleviate such problem.

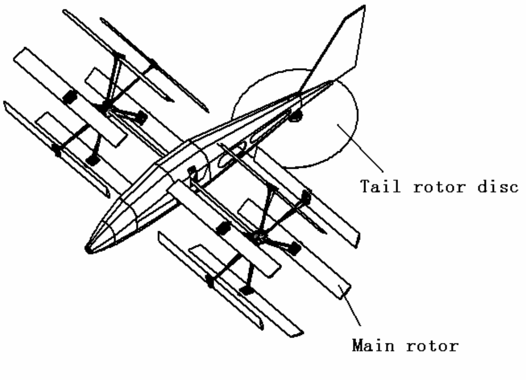

Fig. 1 The cyclogiro

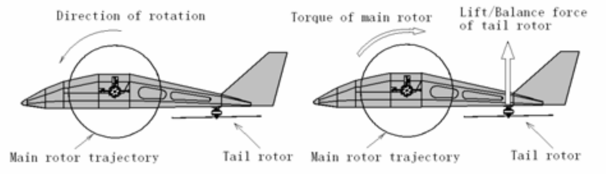

Fig. 2 The balance of main rotor torque

The concept of the cycloidal propellers has been successfully applied on the ships which require high maneuverability, such as tug boats that usually spin horizontally around its centre line. In the 1920's, Frederick Kurt Kirsten first investigated cycloidal propulsion [1]. In the 1930's, John B. Wheatley began work on cycloidal propulsion. He developed a curate blade motion and developed a supporting modeling theory. Wind tunnel tests at the Langley 20-foot wind tunnel were completed using an 8-foot diameter model [2]. In recent years, with the development of modern computer technology, the advanced analytical methods are used in the design of cyclogyro. Therefore the concept of cyclogyro is picked up again. McNabb [1] used classical unsteady aerodynamics theory by Garrick to predict the performance of cycloidal propeller. The research group in Seoul National University conducted both computational and experimental research on cyclogyro [3]. Gil Iosilevskii and Yulval Levy also performed computational and experimental analysis in order to develop a Micro Air Vehicle (MAV) using the concept of cycloidal propeller [4].

Although the concept of cyclogyro has existed almost a century, still more research are needed. It is not fully investigated and there is very big space for improvements and innovations.

In this paper, the effects of taper ratio, aspect ratio (AR.) and winglets to the hovering performance of cycloidal propeller are investigated. The Unsteady Vortex Lattice Method (UVLM) is selected as the analysis method in this paper, since it needs much less computation time than other CFD algorithms, but can solve problems with very complex blade shape and blade motion patterns.

2 The unsteady vortex lattice method

The unsteady vortex lattice method (UVLM) is based on the potential theory which assumes non-viscous and irritation flow. Since the unsteady vortex panel method can deal with the blade wake, the inference of the blades, very complex wing shapes and motion pattern, it enables one to get better understand on the aerodynamics of the cyclogyroes.

The vortex rings are selected as singular element and the wing thickness is neglected for UVLM [5]. The vortex rings are deployed on the wing surfaces and wake sheets. Wake sheet is shed from the trailing segment of the wing trailing edge vortex rings. A new wake line is added at each time step. Since the wake does not carry loads, the wake sheet rolls up with the local fluid velocity. The Neumann boundary condition is applied on each collocation point and a system of linear equations are formed. The circulation distribution on each panel can be obtained by solving these equations. The velocity distribution can then be obtained. Then the Bernoulli function is used to calculate the forces on the wing and hence the lift, drag and torque required to drive the wing can be obtained. To model the wings with arbitrary motion without predefined velocity and simplify the programming, the central difference scheme is used to calculate the kinetic velocity at the collocation points (Eq.1).

$$\begin{pmatrix} U(t) \\ V(t) \\ W(t) \end{pmatrix} = \begin{pmatrix} \dfrac{X(t+1) - X(t-1)}{2 \cdot dt} \\ \dfrac{Y(t+1) - Y(t-1)}{2 \cdot dt} \\ \dfrac{Z(t+1) - Z(t-1)}{2 \cdot dt} \end{pmatrix} \qquad (1)$$

The blade-wake interaction (BWI) problem exists for the cycloidal propellers. But the Biot-Savart's Law used to evaluate the induced velocity at a point due to a line vortex goes to infinity as the distance approaches zero. This result in the instability of the solution and it is especially severe in the case when the vortex wakes are very close to the point of evaluation. The remedy is to replace the singular vortex lines by the vortex line with viscous core model. Many tests over various vortex core models are performed. Finally the viscous vortex core using Scully model (Eq. 2) is selected [6,7].

$$\Delta\vec{v} = \frac{\Gamma}{4\pi}\vec{r}_1 \times \vec{r}_2 \frac{(r_1 + r_2)(1 - \vec{r}_1 \cdot \vec{r}_2 / r_1 r_2)}{r_1^2 r_2^2 - (\vec{r}_1 \cdot \vec{r}_2)^2 + r_c^2 (r_1^2 + r_2^2 - 2\vec{r}_1 \cdot \vec{r}_2)} \qquad (2)$$

3 The investigation of cycloidal propeller design

The efficiency of the cyclogyro in hovering state is investigated in this paper. And the efficiency is define as the power loading of the propeller.

To compare the effects of taper ratio, aspect ratio and winglets, the base line design has to be defined. In this paper, the base line design is defined in Table 1.

Table 1. Parameters of the baseline design

Propeller diameter (mm)	120
Number of blades	6
Blade chord (mm)	25
Rotation speed (RPM)	250 to 1000
Airfoil	NACA 0012

The different design of our test cases is shown in Fig. 3. The base line design is illustrated in Fig. 3a. The tapered blade design is shown in Fig. 3b. The design with larger aspect ratio is shown in Fig. 3c. The design with blade tip plate is shown in Fig. 3d.

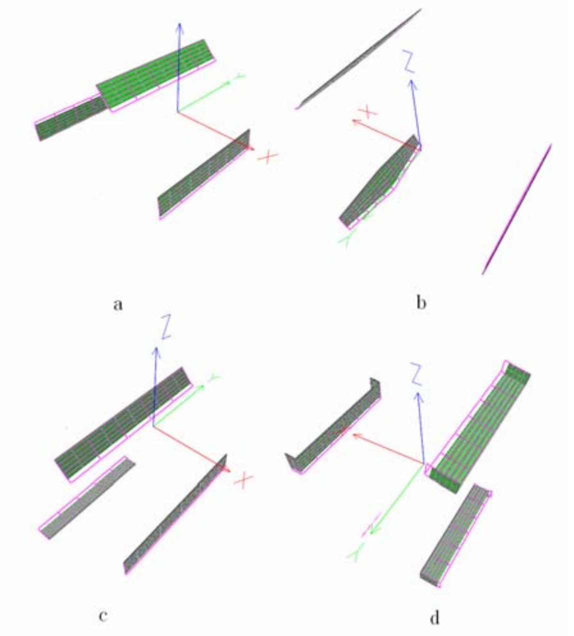

Fig. 3 Blade designs with different features

3.1 The effect of control ring offset

The comparison of power loading for various control ring offsets is shown in Fig. 4. The blade span for these test cases is 320mm.

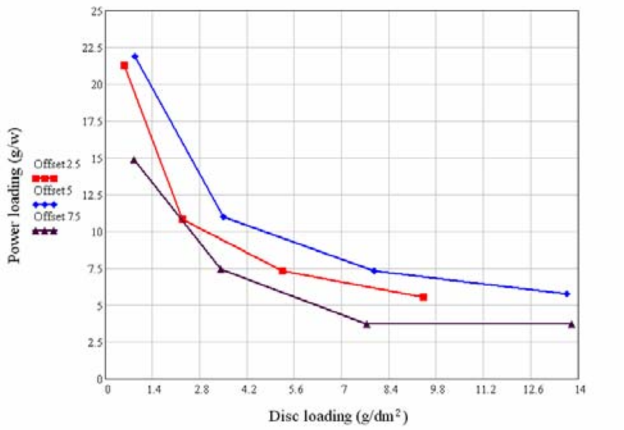

Fig. 4 The effect of control ring offset

From Fig. 4, we can see that the moderate control ring offset has higher hovering efficiency. The design with excessive offset has worst performance. We can also see that the parameter that dominates the power loading is the disc loading. With small enough disc loading, the power loading can be very high.

3.2 The effect of taper ratio

The effect of taper ratio is shown in Fig. 5. The blade span for these test cases is 160mm. The blades in these test cases have the same dimensions except the taper ratio.

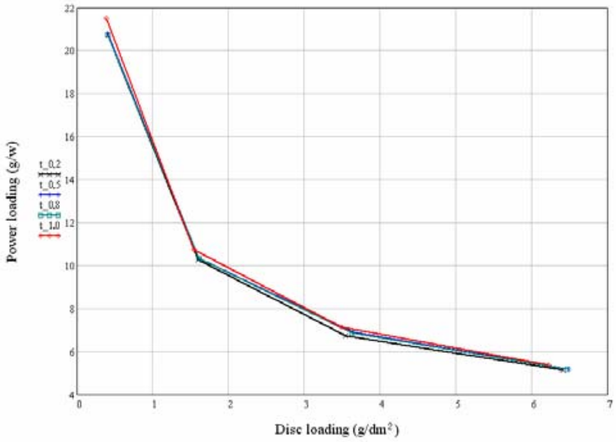

Fig. 5 The effect of taper ratio vary

Unlike the wing traveling in steady state, the taper ratios do not significantly affect the performance of the cycloidal propeller. Therefore, for the cycloidal propeller blades demonstrated in Fig 1, we can use tapered blade to move the blade centre of gravity (C.G) closer to the blade root, where the blade is linked to supporting strut. This can reduce the bending moment that caused by centrifugal force and hence makes the blade structure more durable and lighter.

3.3 The effect of propeller span to diameter ratio

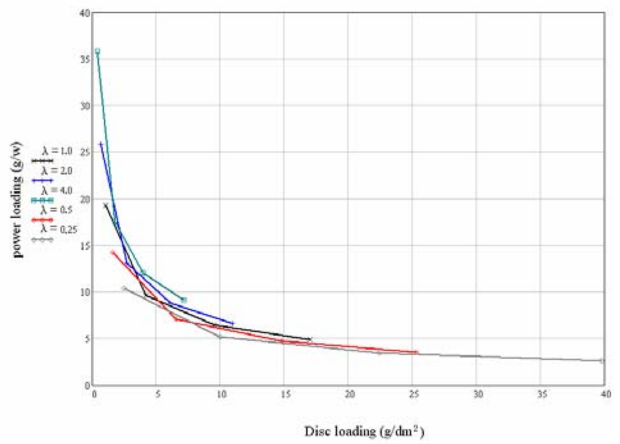

Fig. 6 The effect of propeller span to propeller diameter ratio

In Fig. 6, The propeller span to propeller diameter ratio λ is demonstrated. These test cases have the same disc area but different span to diameter ratio.The span of baseline design for these test cases is 320mm.

According to Fig. 6, for the same disc loading, the propeller with larger span to diameter ratio is more efficient in the hovering state. This is because the aspect ratio of blades will increase for larger span to diameter ratio. The blades with bigger aspect ratio have smaller induced drag.

Howerver, the propeller with smaller radius requires higher rotation speed to generate enough thrust. Since the blade centrifugal force is proportional to square of rotation speed, and the blade will be more slender when λ increases, the blade structure will sustain bigger blade root bending moment. This will cause a heavier structure. One solution to this problem is to bind the blade tip with strings to prevent excessive root bending moment, as shown in Fig 7. In this case, the half blade is equivalent to a cantilever with tip fixed by a hinge. This can greatly reduce the blade tip deflection and structure load with neglectable weight penalty. We have tested such structure on a cycloidal propeller with blade aspect ratio of 12.8. We tied the blade tips with strong fishing thread as thin as hair. The experiment shows that the propeller can work well even the rotation speed reaches 1854 RPM, while the weight of extremely thin fishing thread can be neglected.

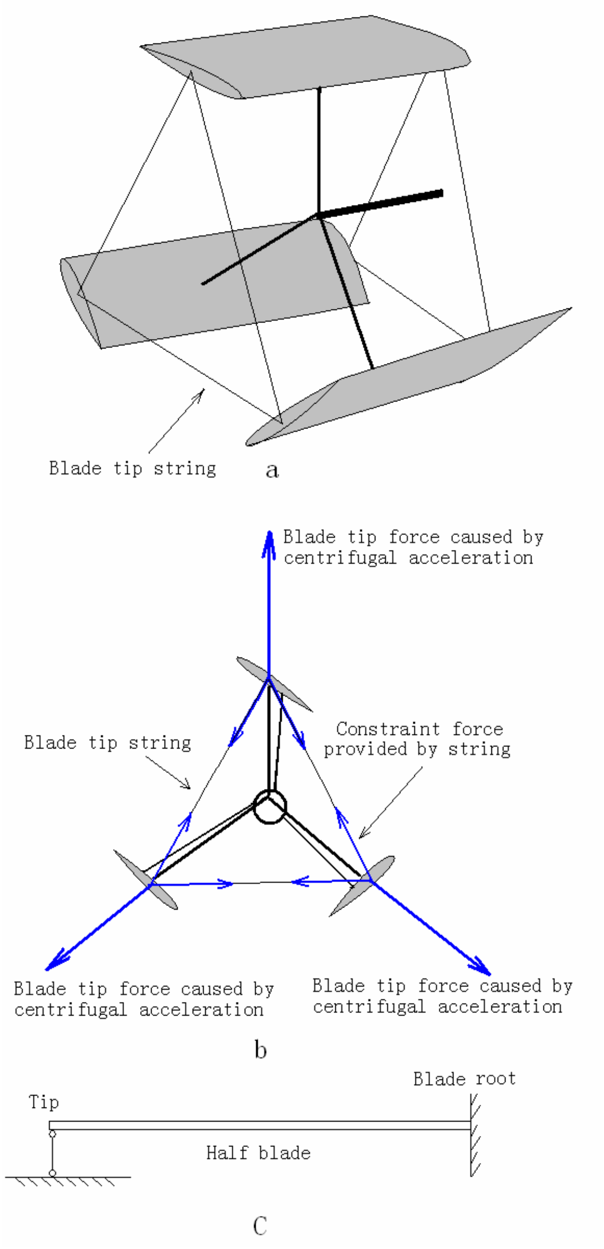

Fig. 7 The blade tip string

3.4 The effect of winglets

The effect of winglets is shown in Fig. 8. The symbol h in Fig 8 is winglet height.

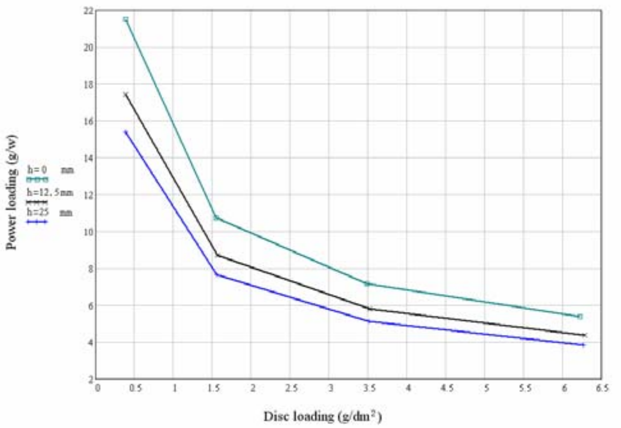

Fig. 8 The effect of blade tip plate

According to Fig. 8, the winglet height do not makes the propeller more efficient. It will also increase the blade tip structure weight and makes the blade bending moment bigger when propeller rotates at high speed.

4 Conclusions

The investigation of various blade design for cycloidal propellers is presented in this paper. The results of comparison shows that just like screw propellers, the disk loading is the dominating factor that affects the power loading when airplane is in the hovering state. By comparing various designs, we can also see that the tapered blade with larger aspect ratio has better performance. However, the winglets do not improve the aerodynamics performance. Therefore it is not suggested for cycloidal propellers.

The new type of blade structure is also presented. It can effectively solve the problem caused by large aspect ratio blade without any weight penalties.

References

[1] Michael Lynn McNabb. *Development of a cycloidal propulsion computer model and comparison with experiment.* PhD thesis, Mississippi State University. Dec 2001

[2] John B. Wheatley and Ray Windler. Wind-tunnel tests of a cyclogyro rotor. *Technical report, Langley Memorial Aeronautical Laboratory*. May 1935. NACA TN-567

[3] Seung Jo Kim, Chul Yong Yun etc, Design and performance tests of cycloidal propulsion systems. *AIAA 2003-1786.* 2003.

[4] Gil Iosievskii, Yuval Levy. Aerodynamics of the cyclogyro, *AIAA-2003-3473, 33rd AIAA Fluid Dynamics Confernece and Exhibit.* 2003

[5] Joseph Katz, Allen Plotkin. *Low Speed Aerodynamics.* Cambridge University Press, 2001

[6] Scully, M. P. Computation of helicopter rotor wake geometry and its influence on rotor harmonic airloads. *MIT, ASPL-TR-178-1.* March 1975

[7] Zhong Yang, *A hybrid flow analysis for rotors in forward flight.* PhD thesis, Georgia Institute of Technology. 2001