Aerodynamic performance enhancement of cycloidal rotor according to blade pivot point movement and preset angle adjustment

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Abstract

This paper describes aerodynamic performance enhancement of cycloidal rotor according to the blade pivot point movement and the blade preset angle adjustment. Cycloidal blade system which consists of several blades rotating about an axis in parallel direction and changing its pitch angle periodically, is a propulsion mechanism of a new concept vertical take off and landing aircraft, cyclocopter. Based on the designed geometry of cyclocopter, numerical analysis was carried out by a general purpose commercial CFD program, STAR-CD. According to this analysis, the efficiency of cycloidal rotor could be improved more than 15% by the introduced methods.

Key Words : Cyclocopter, cycloidal blade system, blade pivot point, preset angle

Introduction

Cyclocopter is a rotary-wing aircraft that produces thrust by a cycloidal blade system [1]. The rotor system consists of several blades rotating about a horizontal axis, which is perpendicular to the direction of normal flight. The rotor blades of the cyclocopter experience a periodic pitch angle variation during rotor rotation as shown at Fig. 1. This feature provides the rotor the capabilities to change the direction and the magnitude of thrust instantly and easily. This characteristic gives the aircraft good maneuverability including VTOL (Vertical Take-off and Landing), hovering and low speed forward flight. Unlike a conventional helicopter rotor, the cycloidal rotor blades operate at a constant speed along the entire blade span, allowing all the blade elements to operate at their peak efficiency and causing the inflow in the spanwise direction to be uniform. Moreover, the cycloidal rotors operate at a much lower rotational speed than conventional helicopter rotors, leading to a very low noise level. This is an essential advantage in various missions such as close observation, flying in an urban environment and military purpose. However, the cycloidal rotor has also several drawbacks caused by its relatively big rotating structure. A conventional helicopter rotor creates a two-dimensional disk, while the cycloidal rotor creates a three-dimensional cylinder. This gives a weight penalty to the cyclocopter when compared to a conventional helicopter rotor.

The cycloidal rotor system was studied at several institutes including NACA and the University of Washington from the 1920's to 1940's [2-7]. Researchers tested cycloidal rotors in a wind tunnel or they built ground test models to investigate their possibilities as an aircraft. Although the performance was good in theory and experimental results supported the theoretical

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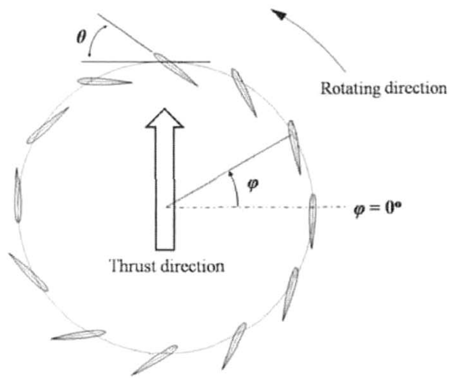


Fig. 1. Cycloidal blade system

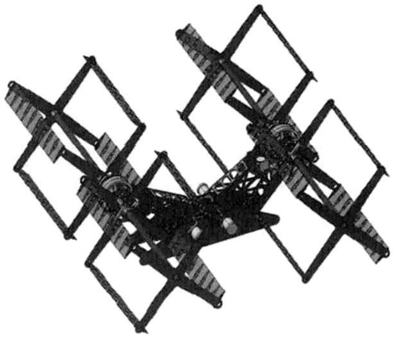


Fig. 2. Cyclocopter

values, all designs failed to be successful in flight. In the late 1990's, when almost 50 years had passed since World War II, the research into the cycloidal mechanism was resumed at Bosch Aerospace [8, 9]. In the ground test of the six-bladed cycloidal rotor, they obtained a high thrust per unit power. The cycloidal blade system was also applied to airship control and a ducted fan in addition to an aircraft by this company. Recently, several other researchers began developing the cycloidal rotor for an aircraft propulsion system [10-13].

The cyclocopter model studied in this research is a small quadrotor type adopting rectangular shape blades as shown at Fig. 2. The design parameters such as rotor radius, blade span and chord length were determined at the previous study [14], and aerodynamic performance enhancement of cycloidal rotor according to the blade pivot point movement and the blade preset angle adjustment based on the designed geometry is described in this paper.

Numerical Setup

For aerodynamic analysis, the commercial CFD program, STAR-CD was used. In this analysis, the moving mesh method should be applied due to periodic pitch angle variations of cycloidal rotor blades; therefore, arbitrary sliding interface technique of STAR-CD was applied. Figure 3 shows the generated mesh used in this study. This two-dimensional mesh consists of approximately 60,000 cells including four rotating blade domains and one rotating rotor domain. In addition, lots of computing is necessary for unsteady and transient simulation. Total computing time of 1,000 time steps was nearly 5,000 seconds using parallel computing of four 3 GHz CPUs. Through this analysis, thrust and required power of cycloidal rotor were calculated. Table 1 lists CFD analysis conditions.

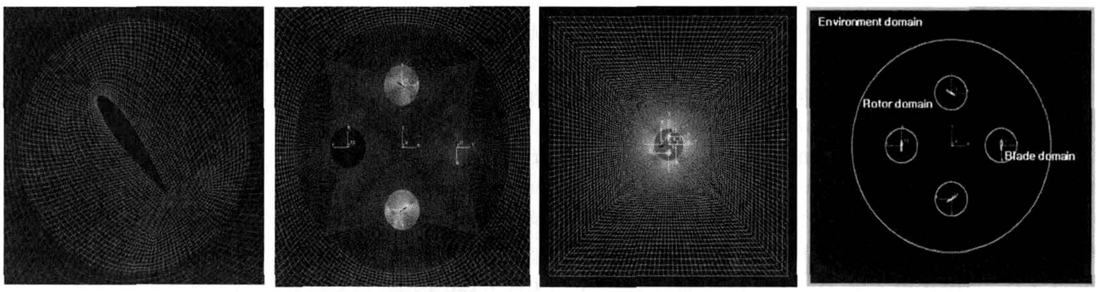


Fig. 3. CFD mesh

Table 1. CFD analysis parameters

Parameter	Value
Analysis type	2D transient
Moving mesh type	Arbitrary sliding interface
Turbulence model	k-ε / high Reynolds
Total number of cells	62,208
Rotating angle per time step of rotor	1.8 deg
Number of time steps	1,000 (5 rev.)

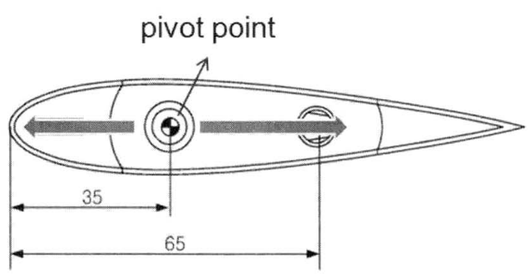


Fig. 4. Pivot point of rotor blade

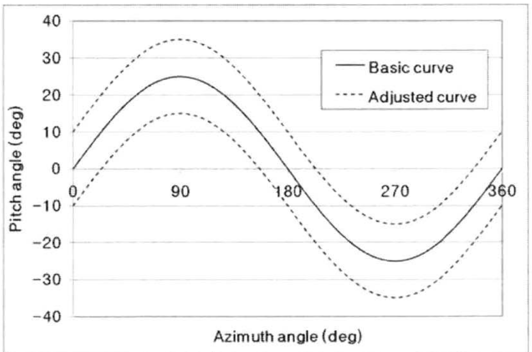


Fig. 5. Preset angle of cycloidal rotor

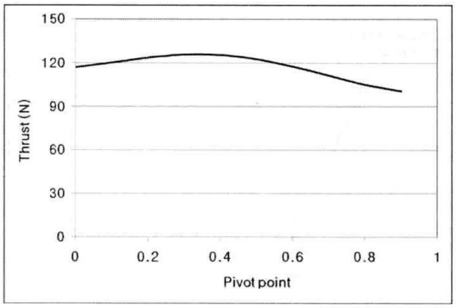
One of the important parameters of cycloidal rotor blade is the location of the pivot point displayed at Fig. 4. Along the airfoil chord line, the blade pivot point could be moved from the leading edge to the trailing edge. To reduce the torsional moment of the blade and to minimize the blade control force, the center of gravity position of the blade should be coincident with the pivot point as shown at Fig. 4. According to the location of the blade pivot point, the CFD mesh of the blade domain is modified.

Another rotor design parameter for aerodynamic performance enhancement is adjustment of the preset pitch angle variation as shown at Fig. 5. The adjusted curve means the movement of all pitch angles in vertical direction. The sign of this movement is defined as plus when the angles are increased. This adjustment could be easily realized by changing the control linkage length.

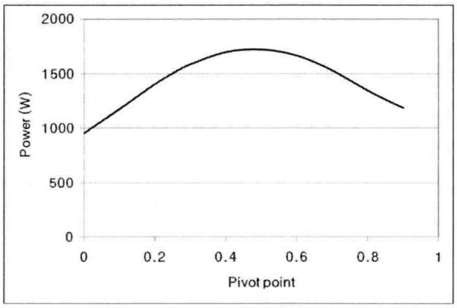
Result and Analysis

Figure 6 shows aerodynamic characteristics of cycloidal rotor blades according to the pivot point location. The operating condition of this analysis is the blade pitch angle of 25° and the rotor rotating speed of 1200 RPM. Thrust is maximized when the blade pivot point is located around 35% position of the airfoil chord line from the leading edge as shown at Fig. 6 (a). Required power becomes the highest around 50% position. From these two graphs, thrust per unit power is determined as Fig. 6 (c); the lowest value around 60% position. This tendency is similar at all other blade pitch angles from 20° to 30°. As a result, the cycloidal rotor becomes more efficient as the blade pivot point is moved close to the leading edge. The practical value considering the location of the center of gravity of the blade is around quarter chord point.

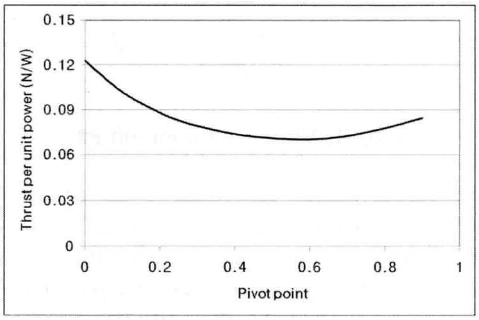
Relating with this phenomenon, the lift on an airfoil oscillating in pitch, in a uniform stream was given theoretically by Theodorsen [15]. According to his equation, the coordinate of axis of oscillation does not affect the amount of the lift generation. However, in cycloidal rotor, the oscillating airfoil experiences the rotor rotating motion, and this is related to the virtual camber effect which is shown at Fig. 8 [1]. Therefore, thrust of cycloidal rotor is changed according to the pivot point movement by the geometrical modification of the virtual camber.



(a) Thrust variation

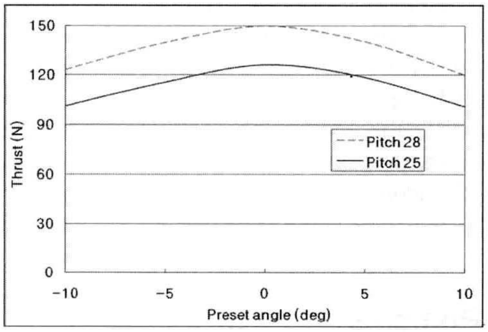


(b) Power variation

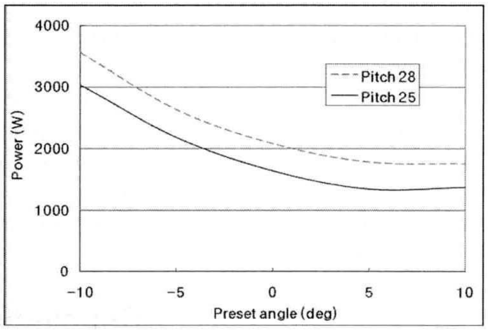


(c) Thrust per unit power variation

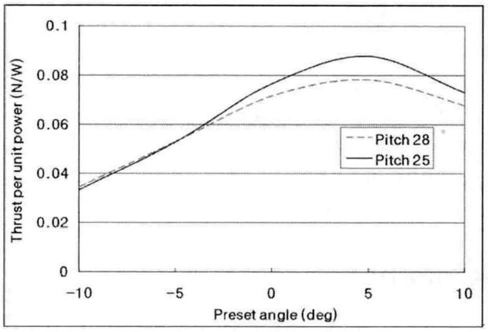
Fig. 6. Aerodynamic characteristics of cycloidal rotor blade according to pivot point location



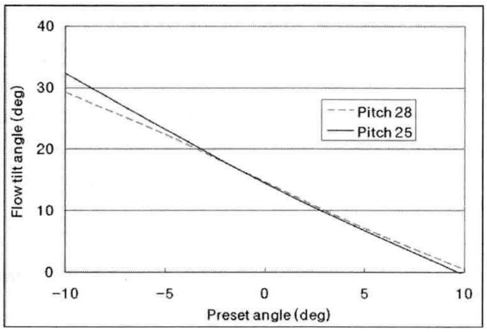
(a) Thrust variation



(b) Power variation



(c) Thrust per unit power variation



(d) Flow tilt angle variation

Fig. 7. Aerodynamic characteristics of cycloidal rotor blade according to preset angle

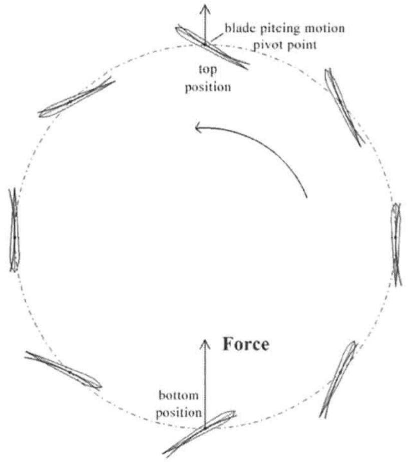


Fig. 8. Virtual camber effect

Figure 7 shows another aerodynamics according to the preset angle adjustment. The rotor rotating speed is the same with the previous analysis as 1200 RPM and the blade pivot point location is 33%. Thrust is maximized when the preset angle is zero and required rotor power is decreased as the preset angle becomes large. Therefore thrust per unit power becomes maximum around the preset angle of 5^{o}. Other important result is the flow tilt angle variation that it becomes smaller as the preset angle increases and almost zero at the preset angle of 10^{o}. This phenomenon is caused by complex reasons; the effective angle of attack considering virtual camber effect and induced flow should be found out and turbulence and pressure distribution are also related. According to the flow characteristics, it is quite different between the preset angle -10^{o} and $+10^{o}$. The fact that large force at large pitch angle could be easily predicted and this is true at both of two cases. However, the flow tilt angle is not same at these two cases. At the upper rotor region of the preset angle -10^{o}, the flow passing the blade is not tilted because the pitch angle is small; on the contrary, it is tilted when the preset angle is $+10^{o}$ due to large pitch angle. At the lower rotor region, the flow is tilted at these two cases by the increased flow velocity caused by the induced flow although the tilted angle is larger at the case of the preset angle -10^{o}. In addition, it is assumed that required rotor power of the preset angle -10^{o} is larger because the effective angle of attack is too high at the lower rotor region.

Concluding Remarks

In this paper, aerodynamic performance enhancement of cycloidal rotor by the blade pivot point movement and the rotor blade preset angle adjustment is described. According to CFD analysis, the power loading of cycloidal rotor could be improved by the blade pivot point movement. When the blade pivot point is moved from the 60% position to the 25% position of the airfoil chord line from the leading edge, the efficiency is improved by 17%. Another improvement is possible by the blade preset angle adjustment. When this angle adjustment becomes $+5^{o}$, the efficiency is improved by 16%. In addition, the flow tilt angle is also changed by this adjustment. This phenomenon is related with virtual camber effect which is a unique characteristic of cycloidal rotor.

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References

1. Yun, C.Y. "A New Vertical Take-off and Landing Aircraft with Cycloidal Blades System: Cyclocopter", Ph.D thesis, Seoul National University, Korea, 2004.

2. Wheatley, J.B., "Simplified Aerodynamic Analysis of the Cyclogiro Rotating-wing System", NACA Technical Notes No.467, August 1933.

3. Wheatley, J.B. and Windler, R., "Wind-tunnel Tests of a Cyclogiro Rotor", NACA Technical Notes No.528, May 1935.

4. Kirsten, F.K., "Cycloidal Propulsion Applied to Aircraft", Transactions of the American Society of Mechanical Engineers, Vol. 50, No. AER-50-12, 1928.

5. Kirsten, F.K., "Cycloidal propulsion in air", Engineering Experiment Station Series Bulletin No. 79, University of Washington, March 1935.

6. Eastman, F.S., Burkheimer, G., and Cotter, W.E., "Wind Tunnel Tests on a High Pitch Cyclogiro", University of Washington Aeronautical Laboratory Report No. 191-A, University of Washington, June 1943.

7. Eastman, F.S., "The Full-Feathering Cyclogiro", University of Washington Aeronautical Laboratory Report No. 317, University of Washington, March 1951.

8. Gibbens, R.P. and Boschma, J.H., "Construction and testing of a new aircraft cycloidal propeller", 13th AIAA Lighter-Than-Air Systems Technology Conference, Norfolk, VA, June 28-July 1, 1999.

9. Boschma, J.H., "Modern Aviation Applications for Cycloidal Propulsion", AIAA, Aircraft, Technology Integration, and Operations Forum, Los Angeles, CA, October 2001.

10. Sirohi, J., Parsons, E. and Chopra, I., "Hover Performance of a Cycloidal Rotor for a Micro Air Vehicle", Journal of the American Helicopter Society, Vol. 52, No. 3, 2007.

11. Iosilevskii, G. and Levy, Y., "Experimental and Numerical Study of Cyclogiro Aerodynamics", AIAA Journal, Vol.44, No.12, 2006.

12. Hu, Y., Lim, K.B. and Hu, W.R., "The research on the performance of cyclogiro", 6th AIAA Aviation Technology, Integration and Operations Conference, Wichita, KS, September 2006.

13. Higashi, Y., Tanaka, K., Emaru, T. and Wang, H.O., "Development of a Cyclogyro-based Flying Robot with Variable Attack Angle Mechanism", IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, October 2006.

14. Lee, C.H., Hwang, I.S., Min, S.Y. and Kim, S.J., "Recent development of VTOL cyclocopter", Tri-University Workshop on Mechanics & Aerospace Engineering, Beijing, China, October 2008.

15. Theodorsen, T., "General Theory of Aerodynamic Instability and the Mechanism of Flutter", NACA Technical Notes No.496, 1935.