DESIGN AND EXPERIMENT OF TWO-ROTORED UAV CYCLOCOPTER

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Abstract

This paper describes design and experimental works of a 100kg-or-heavier cyclocopter. A cyclocopter is a VTOL aircraft that has the Cycloidal Blade Systems (CBS). This system consists of a horizontal axis and several blades, which make it possible to change direction and magnitude of a thrust vector. The cyclocopter developed in this study has two CBS rotors and a horizontal tail rotor. To reduce drag, the cyclocopter has end plates, improved shape of trailing edge, and control arm. A new concept of control mechanism is proposed that uses a cam path. A stable hovering flight test is performed under tethered condition.

1 Introduction

In these days, Unmanned Aerial Vehicles (UAVs) are widely used in various fields. While some UAVs are fixed-wing airplane type, many of them are in Vertical Take-off and Landing (VTOL) type in order to use under the particular environment such as insufficient take-off and landing spaces. The cycloidal blade system which can be described as a horizontal rotary wing offers unique ability to change the direction of thrust that is perpendicular to rotating axis, almost instantly. Figure 1 shows a typical pitching motion of a normal flight. The blades at the top and the bottom positions produce upward force with positive angle of attack. On the other hand, the blades on the left and the right positions produce negligible amount of force, because the blades have little angle of attack.

Cycloidal rotor system was studied at several institutes including NACA and University of Washington from 1920's to 1940's [1-6]. The rotor performance prediction based on this theory was also compared with wind tunnel test results [2]. However, researches in this field had hardly been performed for decades. In the late 1990's, the research about the cycloidal blade system was restudied at Bosch Aerospace [7, 8]. In December 2011 a team at the University of Maryland successfully system revived at a twin-rotor MAV-scale cyclocopter and demonstrated a stable hover flight [9-12].

1.1 UAV cyclocopter with 2rotor

Cyclocopter is adopted by CBS(Cycloidal Blade System) which consists of several blades and horizontal main axis. The thrust of CBS is affected by blade's rotating speed, magnitude of maximum pitch angle, and its phase angle.

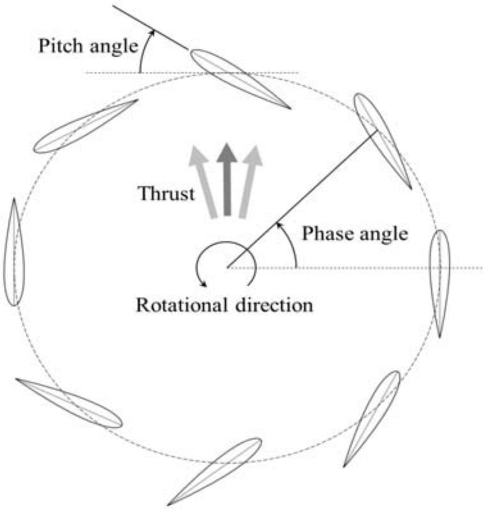

Fig. 1 Cycloidal Blade System

Some of MAV-sized cyclocopters are controlled by rotating speed of the main rotor, but this is not possible in larger UAV-sized because of a larger rotor inertia. In this study, the rotational speed of the main rotor is constant during flight. Thus, the attitude is controlled only by maximum pitch and phase angles.

The cyclocopters are classified into 2-rotor system and 4-rotor systems. Generally, the 4-rotor system's control logic is similar to a conventional quad-copter. However, that of 2-rotor system is more complicated because it has gyro effect and larger main rotors. Although, control logic is complicated, 2-rotor system is lighter than 4-rotor system. Also, 2-rotor system has compact gear-box and power mechanism structure than 4-rotor system. Flow streams around are less interfered in 2-rotor system.

2 Design of Experiment Object Model

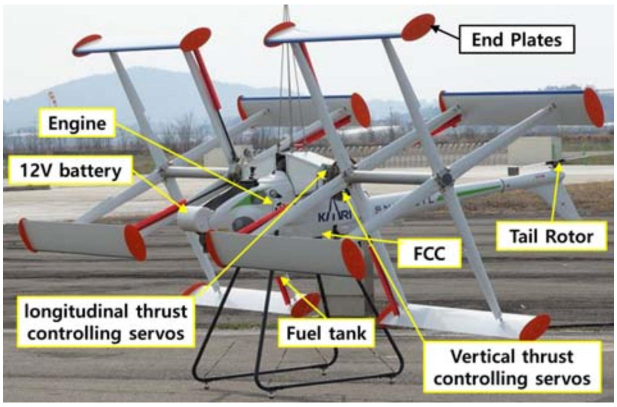

Fig. 2 Designed Cyclocopter

2.1 Structural Design

The present paper describes design and development of 100kg class UAV cyclocopter as shown in Figure 2. It has one tail rotor and two main rotors which rotate in same direction. The anti-torque tail rotor is used as a conventional propeller whose thrust is adjusted by its pitch angle. The two main rotors produce thrust only by adjusting pitch and phase angles, and the rotating speed is fixed at 400rpm.

The tail rotor and the main rotors are connected by a belt and a pulley. The tail rotor's rotating speed and diameter are 5,320rpm and 574mm, respectively. The vehicle has a longitudinal dimension of 3.15 meters, a lateral dimension of 4.2 meters, a height of 2.3 meters and a weight of 110kg. Each of main rotors has a diameter of 2 meters and a span length of 1.5 meters that consists of 4 blades. The main rotors and the tail rotor are operated by a 4-stroke gasoline rotary engine. The rotary engine, XR50 model, is made by AIXRO in Germany. The maximum power is 33kW at 7,500rpm but the continuous power is 22.5kW at 6,000rpm that considers cooling and durability. The advantages of this engine are lack of vibration due to balanced rotating masses, compact design, low emissions, and consistent torque. Therefore, this engine is suitable for achieving stable flight and understanding characteristics of the experimental vehicle. Engine performance graph in figure 3 shows that the torque is almost consistent between 4,000 to 8,000rpm. An alternator is installed for charging 12V battery which is used for electric equipment. Thus, this vehicle is hardly necessary to charge by external electrical power, and it only consumes gasoline. Figure 4 shows the power train. The coolant pump and the radiator are installed for water cooling system. A rotorcraft has worse cooling condition than an airplane especially at a stationary flight. Therefore, a water cooling system is preferred even though the system is complicated.

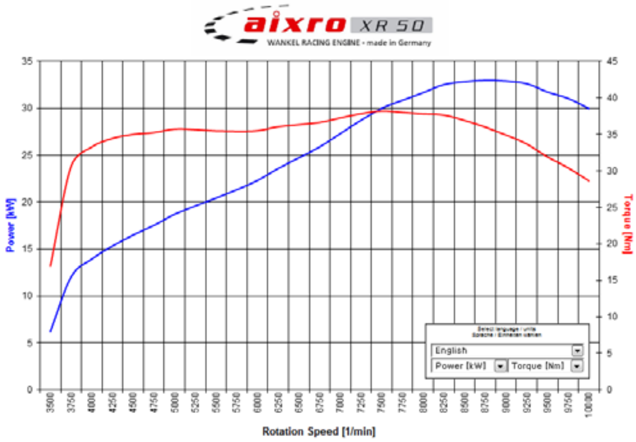

Fig. 3 Engine performance data

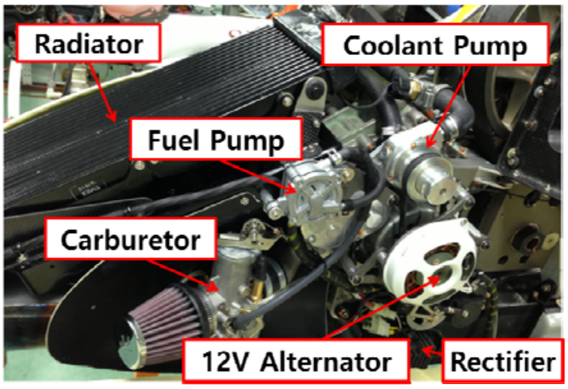

Fig. 4 Power train of cyclocopter

Previous version of blades from the previous version are 1-meter long. They are vulnerable to bending stress while operating. To reduce its stress, the blade length is increased to inboard and outboard by 150mm and 350mm, respectively. As a result, total length of blades is 1.5m long and the bending stress is reduced by 28%. Figure 5 shows bending moment graph of both 1.5m and 1m length blades. Furthermore, the main structure of blades are made up of two C-shaped carbon composite material spars. Figure 6 shows the blade it in section.

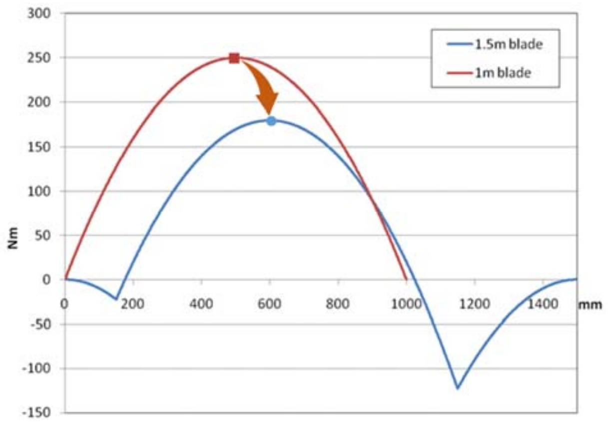

Fig. 3 Bending moment about the blades

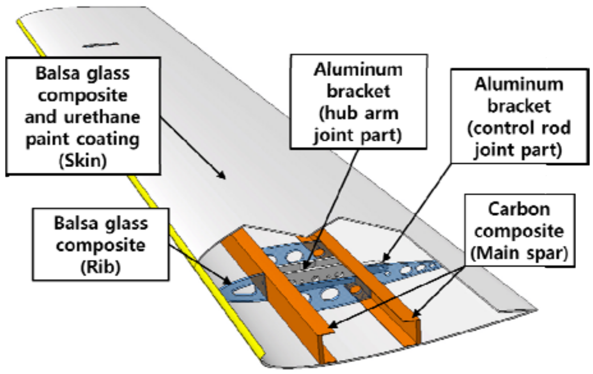

Fig. 4 The cross-sectional drawing of the main blade

Table 1 Design parameters for the UAV cyclcopter

Parameters	Value
Rotor diameter	2,000mm
Blade Span length	1,500mm
Blade chord length	247mm
Airfoil	NACA0018
Main rotor RPM	420RPM
Max. Pitch angle	0~35º
Length with rotors	3,152mm
Height	2,310mm
Width	4,200mm
Total weight	110kg
Chamber volume of engine	294cc

2.2 Aerodynamic Design

To reduce drag force, the cyclocopter is fitted with end-plates. The two end-plates are attached to the each blades of which height is 125mm. Difference of the drag coefficient is calculated by equation 1 which is derived by "NACA report No. 267, PAUL E. HEMKE" [13]. Let $C_L = 2\pi\alpha$, the result is $\Delta C_D = 0.25146\alpha^2$. (neglect profile drag) Therefore, the total difference of the drag power is 1,150W, 1.54HP when the maximum pitch angle is 15°.

$$\Delta C_D = \frac{{C_L}^2 S}{\pi b^2} \frac{1.66\left(\frac{2h}{b}\right)}{1 + 1.66\left(\frac{2h}{b}\right)} - 2C_F\left(\frac{2h}{b}\right) \qquad (1)$$

On the other hand, the cross section of the hub-arms and the linkage-arms are Ellipse and cylinder, respectively. To reduce drag force, its cross section is improved to have an airfoil shape. Generally, drag coefficient of an ellipse or cylinder is much larger than an airfoil ($C_{d,ellipse} \cong 0.6$, $C_{d,cylinder} \cong 1.10$, $C_{d,airfoil} \cong 0.045$). The Power loss due to rotations of the hub-arms and linkage-arms is calculated as below,

$$Power\ loss = \int \frac{1}{2} C_d \rho (r\Omega)^2 rt\, dr \qquad (2)$$

The power loss is 5.65HP and it can be reduced to 0.62HP by improving the cross-sectional shape.

2.3 Design of Tail-rotor

Torque of the main rotor should be known to design the tail rotor. Firstly, consumed power is estimated from previous experiment data and the CFD result. Table 2 shows the data related to the design of the tail rotor system. Equation 3 is the torque equilibrium formula.

$$\frac{Main\ rotor\ consume\ power}{Main\ rotor\ rotating\ speed} = Main\ rotor\ thrust \times Main\ rotor\ position + Tail\ rotor\ thrust \times Tail\ rotor\ position \qquad (3)$$

Table 2 Tail-rotor design value

Parameters	Value
Main rotor consume power(HP)	22
Main rotor rotation speed(RPM)	420
Main rotor position from CG (mm)	50
Tail rotor position from CG (mm)	2,250

Thus, the tail rotor should produce 14.7kgf thrust for the cyclocopter staying at a stable position. To be specific, additional force for pitching control should be considered on top of the calculated torque.

2.4 Design of Power Transmission

Cyclocopter rotors are actuated by the 4-stroke rotary engine. This engine runs on regular gasoline and continuously outputs a power of 29HP. In general, a rotary-type engine vibrates less than a reciprocating engine. Therefore, more stable flight is expected with a rotary-type engine. When the engine runs at 6,000rpm, the reduction ratio of 14.3:1 is required for the main rotor to rotate at 420rpm. For this reduction mechanism, a timing belt-pulley and regular gears are applied.

The rotating shaft connected with the belt-pulley device is AL6063 metal pipe with a diameter of 77 mm and a thickness of 3.5mm. A cantilever type power transmission shaft should support a thrust of 50 kgf each, which is a relatively small amount. Therefore, static deflection does not cause a problem; however, the shaft whirling could be an issue because the weight is applied at the tip of the shaft. Whirling speed of shaft is calculated by following equations [14].

$$\Omega^2 = \Omega_0^2 \left(1 - \frac{4 A p_0 l^2}{\pi^2 EI} \right) \qquad (4)$$

$$\Omega_0 = \frac{3.67}{l^2} \sqrt{\frac{EI}{\rho A}} \qquad (5)$$

The whirling speed (Ω) of the shaft is calculated as 3,633rpm which is higher than the designed rotating speed. Therefore, the current main shaft can be used without whirling.

3 Experiment

3.1 Ground test

The purpose of the ground test is thrust measurement and verification of analysis results. The ground test bed consists of steel structures and 5 load cells which are tension-compression type and each load cell can measure ±100kgf (see Figure 7). The 3 load cells are placed in triangular shape to measure vertical, roll, pitch direction of forces. The fourth load cell measures forward and backward direction of force, the last one measures yaw direction of force. Therefore, this test bed can measure all force components of the cyclocopter. The maximum lift force is 130kgf as shown in figure 8. The measuring instrument is cDAQ, National Instruments Company. The thrust is measured once per second and averaged over 10 points. The measured values (points in Figure 8) are smaller than analytical values. This is partly due to 3-dimensional effect and non- ideal environment. Note here that analytical value is from 2-dimensional analysis.

Fig. 5 Ground test on the test bed

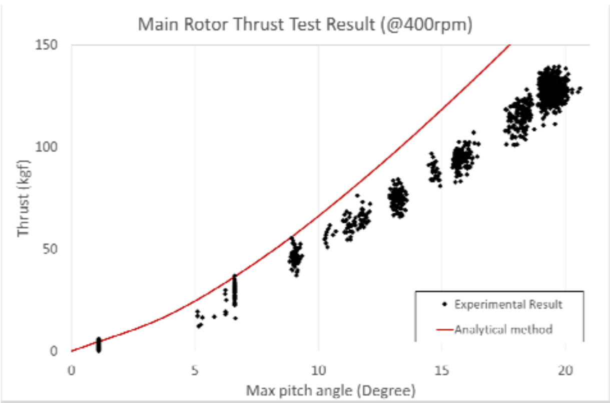

Fig. 6 Variation of thrust with pitch angle

3.2 Tethered flight test

Figure 9 shows the manufactured cyclocopter which is tethered to the tower crane. The cyclocopter with FCS (Flight Control System) is tested in SCAS (Stability Control Augmentation System) mode. Pitching, rolling, and yawing gain are tuned one by one.

Fig. 7 Tethering flight test

Figure 10 shows the characteristics of throttle, pitch and roll. The pitch and roll commands are very similar to the response. It means that this vehicle has sufficient flight control performance. Figure 11 shows coupled rolling and yawing motions due to gyroscopic precession. The graph of rolling and yawing rates shows similar tendency. Therefore, feedback values of the rolling and yawing motions are also coupled. Finally, stable hover flight is carried out under a tethered condition. Figure 12 shows stable motion of the rolling once stable hovering flight is achieved.

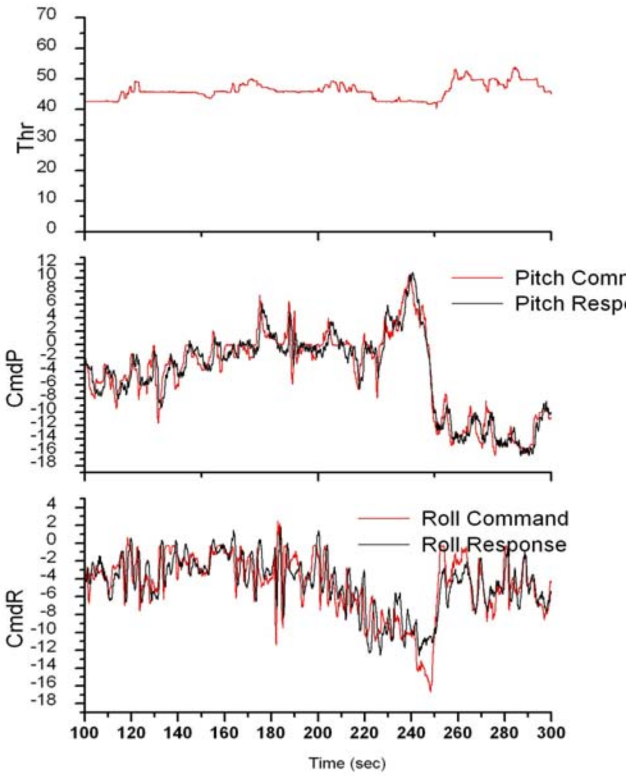

Fig. 8 Flight characteristics under S/CAS mode

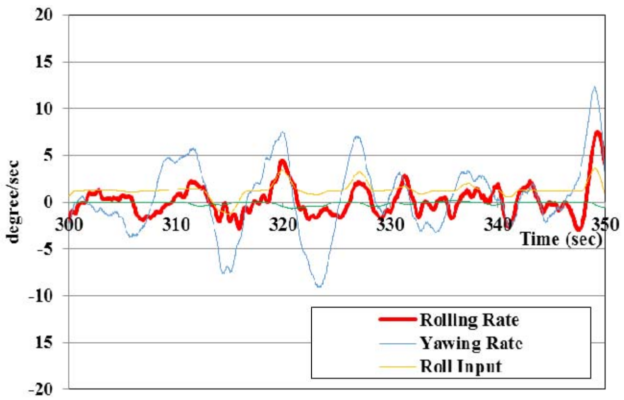

Fig. 9 Graph of the rolling and yawing motion

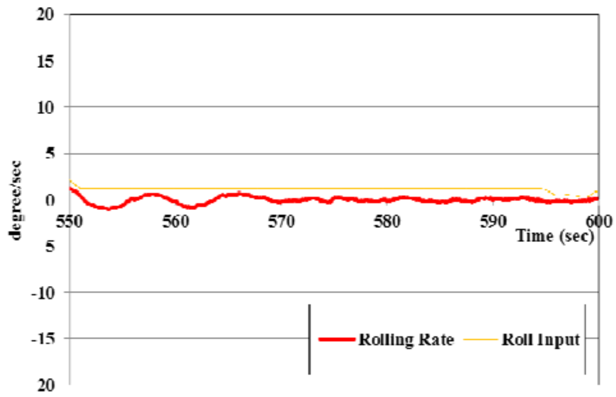

Fig. 10 Stable rolling motion with adjusting gain

4 Conclusions

Fig. 11 Stable hover flight of the cyclocopter

Figure 13 shows stable flight test of the cyclocopter at tethered condition. A stable hovering flight could be demonstrated without any strings; however, it wasn't performed due to safety reasons especially during take-off and landing. The payload of this cyclocopter is 2kg which is lower than expected due to the lack of engine power. This cyclocopter could be enough to be used as a UAV system once a larger engine is equipped.

References

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

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

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

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

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

[6] Eastman, F.S., "The Full-Feathering Cyclogiro," UWAL Report No. 317, University of Washington Aeronautical Laboratory, Seattle, Washington, March 1951.

[7] 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.

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

[9] Benedict, M., Chopra, I., Ramasamy, M. and Leishman, J.G., "Experimental Investigation of the Cycloidal-Rotor Concept for a Hovering Micro Air Vehicle," American Helicopter Society 64th Annual Forum Proceedings, April 29 - May 2, 2008.

[10] Benedict, M., Ramasamy, M., and Chopra, I., "Improving the Aerodynamic Performance of Micro-air-vehicle-scale Cycloidal Rotor: an Experimental Approach." Journal of Aircraft, Vol. 47, (4), 2010, pp. 1117-1125.

[11] Benedict, M., Ramasamy, M., Chopra, I., and Leishman, J. G., "Performance of a Cycloidal Rotor Concept for Micro Air Vehicle Applications," Journal of the American Helicopter Society, Vol. 55, (2), April 2010, Paper 022002.

[12] Benedict, M., Gupta, R., and Chopra, I., "Design, Development and Flight Testing of a Twin-Rotor Cyclocopter Micro Air Vehicle," American Helicopter Society 67th Annual Forum Proceedings, Virginia Beach, VA, 2011.

[13] PAUL E. HEMKE, "Drag of Wings With End Plates" Langley Memorial Aeronautical Laboratory, National Advisory Committee for Aeronautics, Langley Field, VA, January 20, 1927.

[14] D. E. Newland. 1971. "Whirling of a Cantilever Elastic Shaft Subjected to External Pressure". In:Journal Mechanical Engineering Science, Vol. 14 No.1,pp. 11-1

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