Design of two-rotored UAV Cyclocopter

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Abstract
This paper describes the design and experimental works of a 100kg-or-heavier cyclocopter. A cyclocopter is a VTOL aircraft and it has the Cycloidal Blade Systems (CBS). This system consisted 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 estimate amount of generated thrust and required power, 2-demensional CFD analyses has preceded. The 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 space for take-off and landing. The cycloidal blade system which can be described as a horizontal rotary wing offers a unique ability to change the direction of thrust that perpendicular to rotating axis, almost instantly. Figure 6 shows a typical pitching motion of 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 generate on the left and the right positions produces small 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, reseaches 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].

From the year 2000, several shapes of cycloidal rotor systems and their control mechanisms were studied and developed for ensuring hovering capability of cyclocopter by authors at Seoul National University. Single rotor experiment was conducted to verify the potential of a cyclocopter by VTOL air vehicle. Our team develop two different scales UAV cyclocopter simultaneously. Figure 1 shows small scale UAV cyclocopters and figure 2 shows large scale UAV cyclocopters. Fifth version of the small scale UAV cyclocopter successfully fulfilled a stable hover and low speed level flights [13].

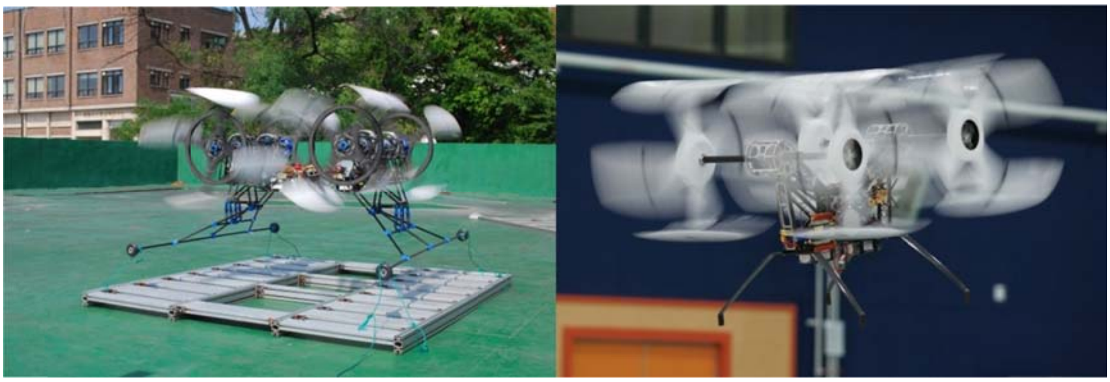

Figure 1: Previous researches of small scale UAV cyclocopter

Figure 2: Previous researches of UAV cyclocopter

2. CFD Analysis

Based on the previous research, a two-rotored cyclocopter is conceptually proposed [14]. A transmission of two-rotored cyclocopter is more efficient than that four-rotored one because of shorter distance between the rotor and the engine. Due to fewer number of rotors, their size is larger than the four-rotored case. Its dimension is appropriate value through similar solidity [15]. Figure 3 shows a sketch of the two-rotored cyclocopter developed in this study.

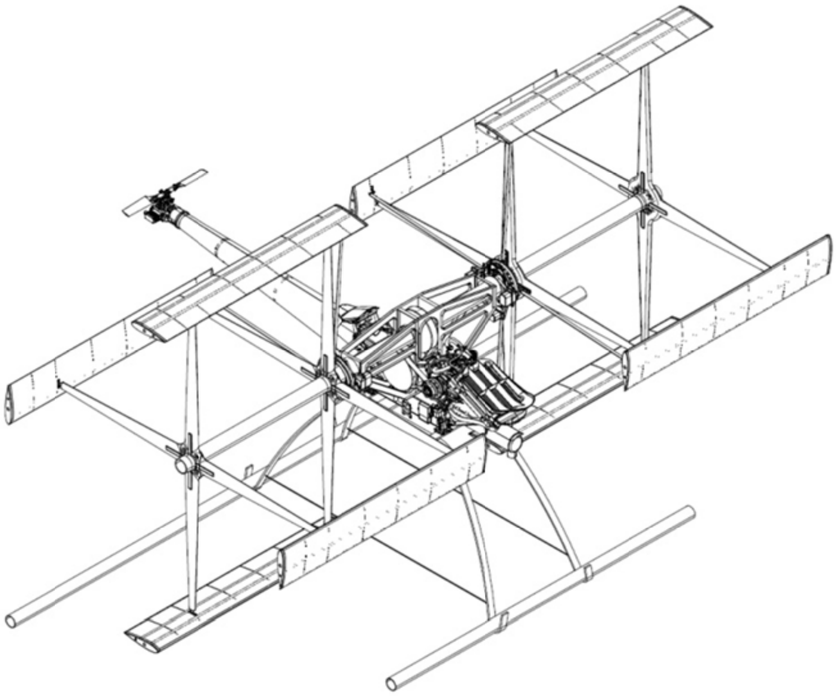

Figure 3: Designed cyclocopter

2-demensional CFD (Computational Fluid Dynamics) analysis is performed using ANSYS FLUENT program to determine the aerodynamic performance and to verify efficiency of the system. Table1 and 2 are design and analysis parameters, respectively. Figure 4 shows velocity results at which maximum pitch angle is 25°.

Table 1: Design parameters of UAV cyclcopter

	Specifications
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

Table 2: Analysis condition

	Specifications
Analysis type	2D Transient
Mesh type	Quadrilateral (Iso & Paver)
Total number of cells	79,676
Rotating angle / time step	1.8 °
Number of domains	6
Moving mesh type	Sliding Mesh
Turbulence model	K-epsilon
Variables	Pitch angle
Number of time steps	20,000
Analysis time	12hrs (@2.66Ghz)

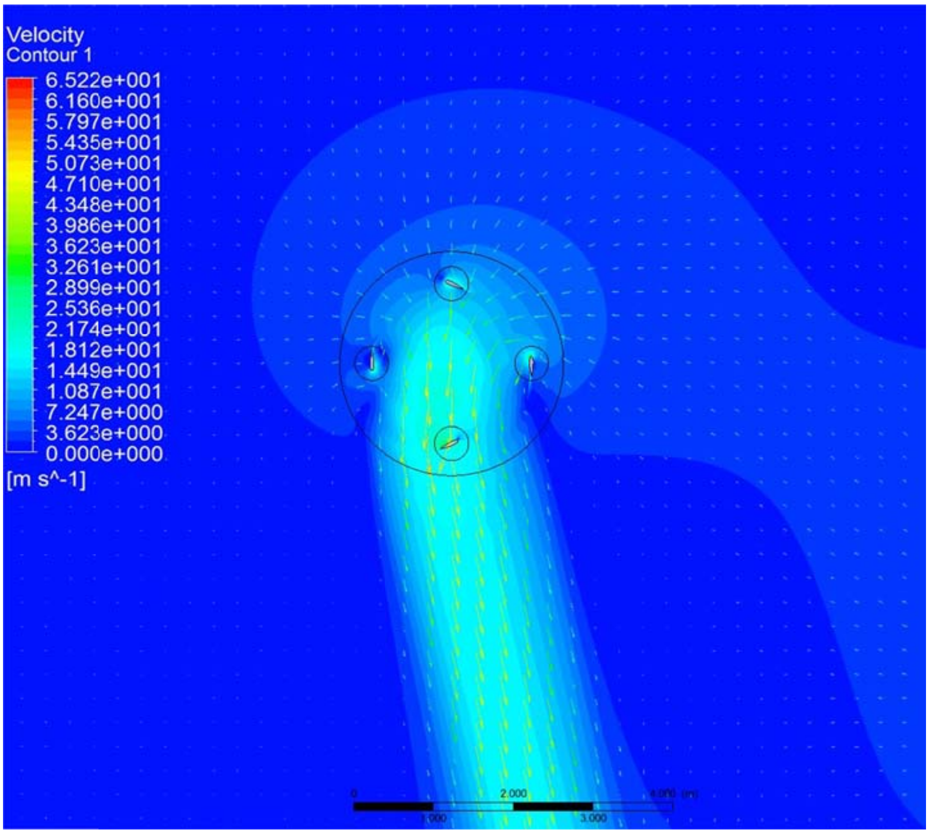

Figure 4: CFD analysis result (@25°)

3. Design of Cyclocopter

3.1 Design of Control Mechanism

Cycloidal blade system offers controllability of thrust direction and its magnitude. In this research, Rolling, pitching and yawing motions can be manoeuvred independently. Figure 5 shows its attitude control scheme.

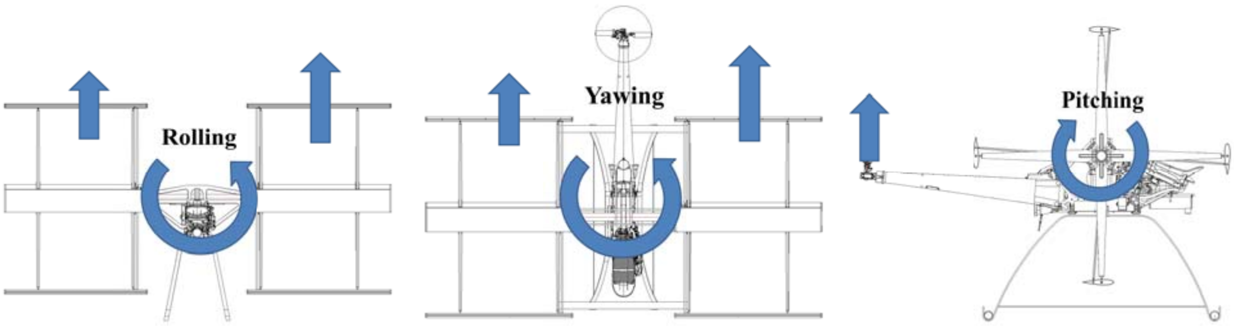

Figure 5: Scheme of attitude control of two-rotored cyclocopter

Control mechanisms of previous cyclocopters are not axisymmetric as indicated in figure 6. Usually, only one control rod is fixed to rotate inner-ring while others are pinned. Therefore, the pitch angle paths are not perfectly identical to each other (Figure 7). In fact, this repetitive difference creates vibrations and noises. Figure 8 shows the cyclocopter of previously developed by the authors and its control mechanism. Recently, the research group in University of Mayland developed a control mechanism that offers identical pitch angle paths [9]. However, this mechanism is located to the tip of main axis, which might be a structural weak point. Moreover, the system is not structurally axisymmetric because the control links are assembled in consecutive order.
The control mechanism developed in this research has perfectly identical pitch control path as well as structural axisymmetric. It is composed of a cam-path ring, LM guide and cam-bearings.

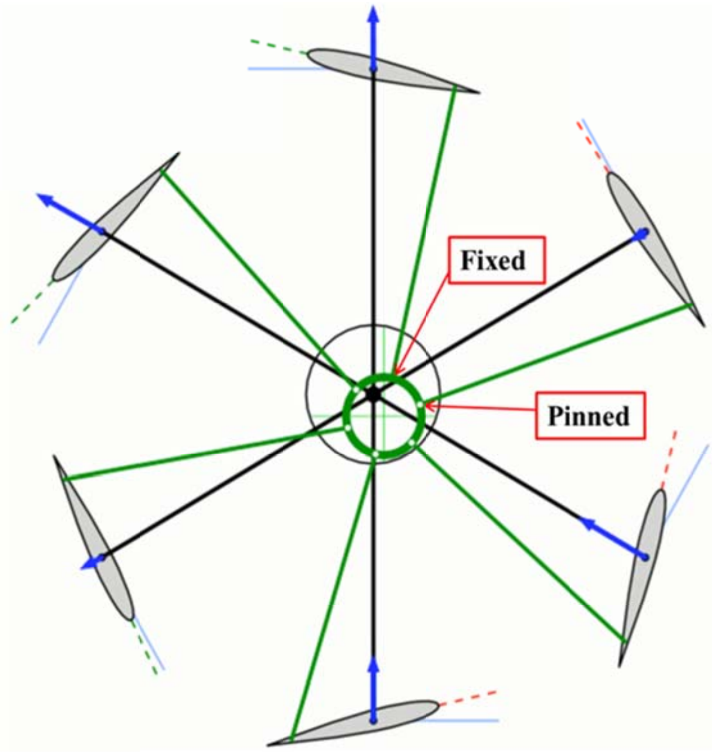

Figure 6: Cycloidal blade system [17]

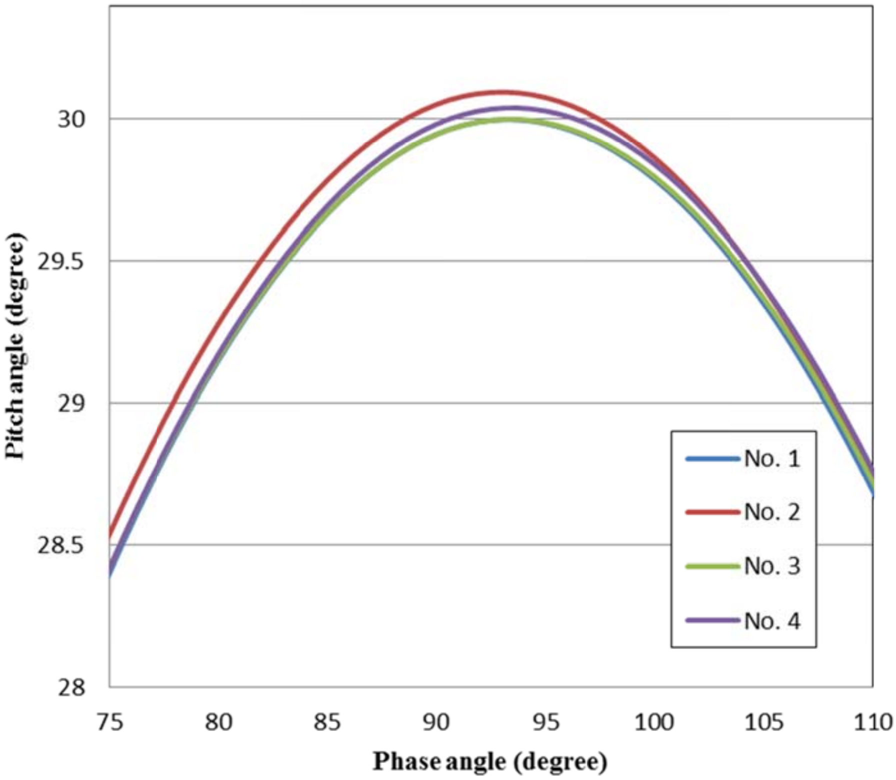

Figure 7: Pitch angle path of cycloidal blade system

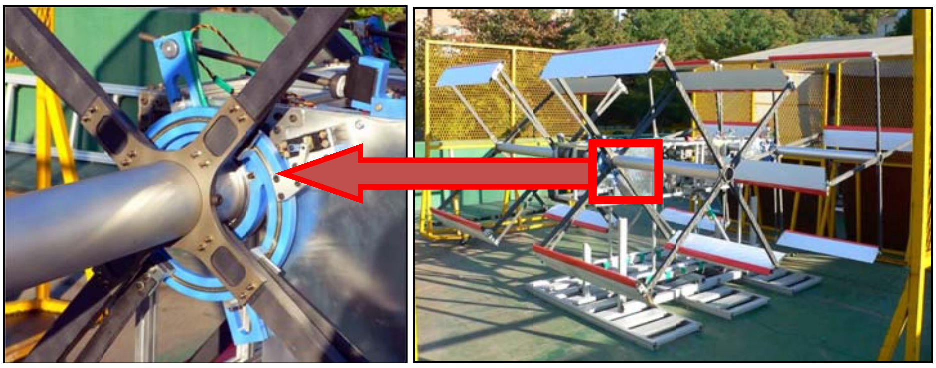

Figure 8: Control mechanism of previous UAV cyclocopter

The servo actuators control the amount of thrust by moving up-and-down and back-and-forth directions of the cam-path ring. Figure 9 shows components of the control mechanism and servo actuators.

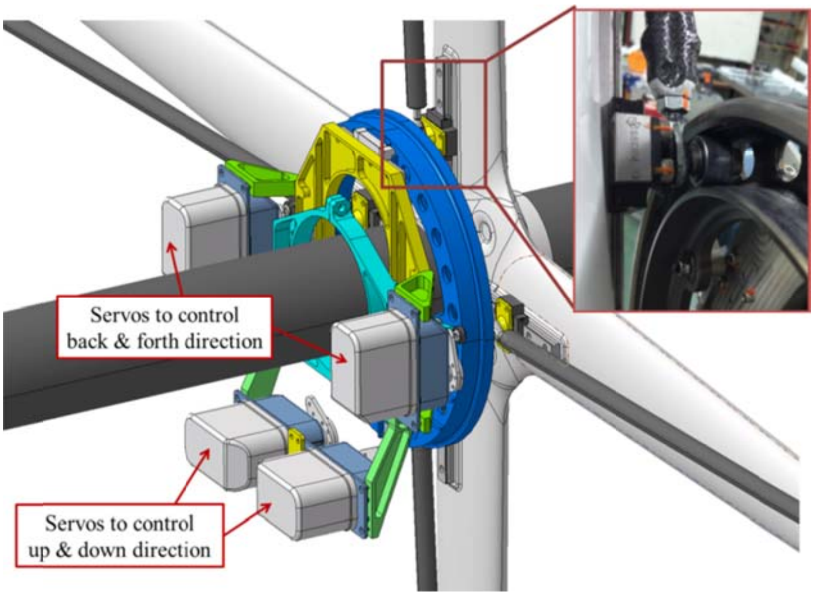

Figure 9: Control mechanism of new designed UAV cyclocopter

3.2 Design of Tail-rotor

Torque of main rotor should be known to design the tail rotor. Firstly, consumed power is estimated from previous experiment data and the CFD result. Table 3 shows the data related to the design of the tail rotor system. Equation 1 is the torque equilibrium formula.

Table 3: Tail-rotor design value

	Specifications
Main rotor consume power(HP)	22
Main rotor rotation speed(RPM)	420
Main rotor position from CG [a] (mm)	50
Tail rotor position from CG [a] (mm)	2,250

[a] Center of Gravity

$$\frac{Main\ rotor\ consume\ power}{Main\ rotor\ rotating\ speed} = Main\ rotor\ thrust\ \times Main\ rotor\ position\ + \\ Tail\ rotor\ thrust\ \times Tail\ rotor\ position \quad \textbf{(1)}$$

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.

3.3 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 continuously. A rotary-type engine vibrates less than a reciprocating engine. Therefore, more stable flight is expected with the rotary-type engine. When the engine runs at 6,000rpm, the reduction ratio of 14.3:1 is required for the main rotor rotation of 420rpm. For this reduction mechanism, timing belt-pulley and regular gears are applied.

The rotating shaft connected with belt-pulley device is AL6063 metal pipe with diameter of 77 mm and thickness of 3.5mm. The cantilever type power transmission shaft should support the 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 [18].

$$\Omega^2 = \Omega_0^2\left(1 - \frac{4Ap_0 l^2}{\pi^2 EI}\right) \quad \textbf{(2)}$$

$$\Omega_0 = \frac{3.67}{l^2}\sqrt{\frac{EI}{\rho A}} \quad \textbf{(3)}$$

From above equations, Ω is whirling speed of shaft. Ω_0 is whirling speed of shaft with zero external pressure. And p_0 is pressure at free end of shaft. Therefore, the whirling speed of the shaft is calculated as 3,633rpm which is higher speed than the designed rotating speed.

4. Experiments

4.1 Thrust Test

Figure 10 shows thrust test on the ground. The three load cells are equipped at the bottom of the main body. The thrust test result is described as figure 11. Experiment data value is bigger than CFD result value. The difference is attributed to the 2D assumption of CFD analysis, experimental error and ground effect. Once the magnitudes of the thrusts of the main and tail rotors are confirmed to be larger than the vehicle weight, tethered flight test is performed.

Figure 10: Ground test of the cyclocopter

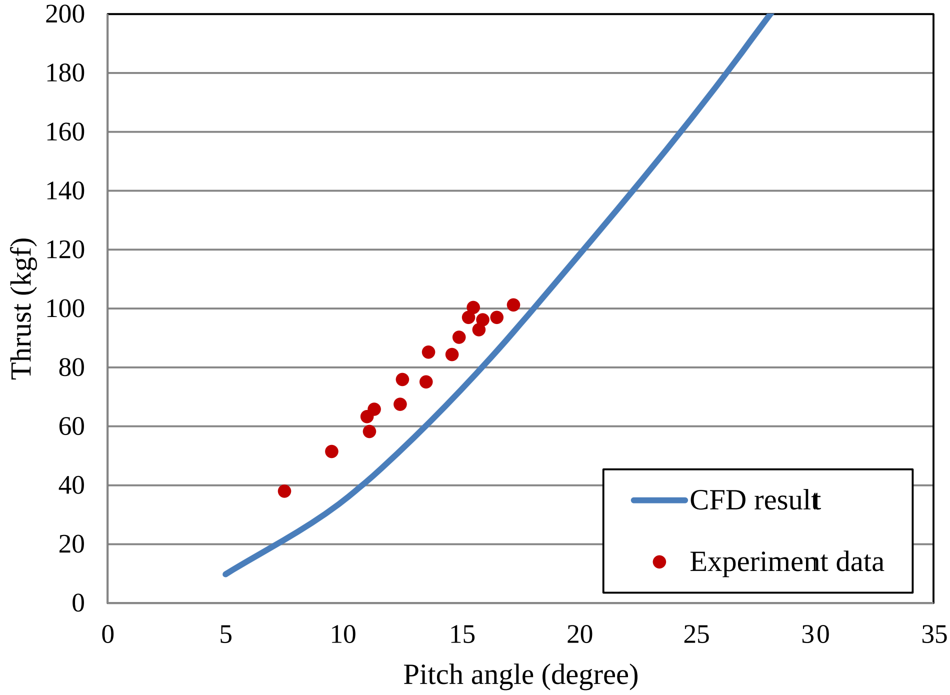

Figure 11: Experiment data vs. CFD result (main rotor only)

4.2 Tethered Flight Test

Figure 12 shows the developed 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.

Figure 12: Tethering flight test

Figure 13 shows coupled rolling and yawing motions because of gyroscopic precession. The graph of rolling and yawing rate shows similar tendency. Therefore, feedback values of the rolling and yawing motions are also coupled. Finally, stable hover flight is carried out under the tethered condition. Figure 14 shows stable motion of the rolling and yawing once stable hovering flight is achieved.

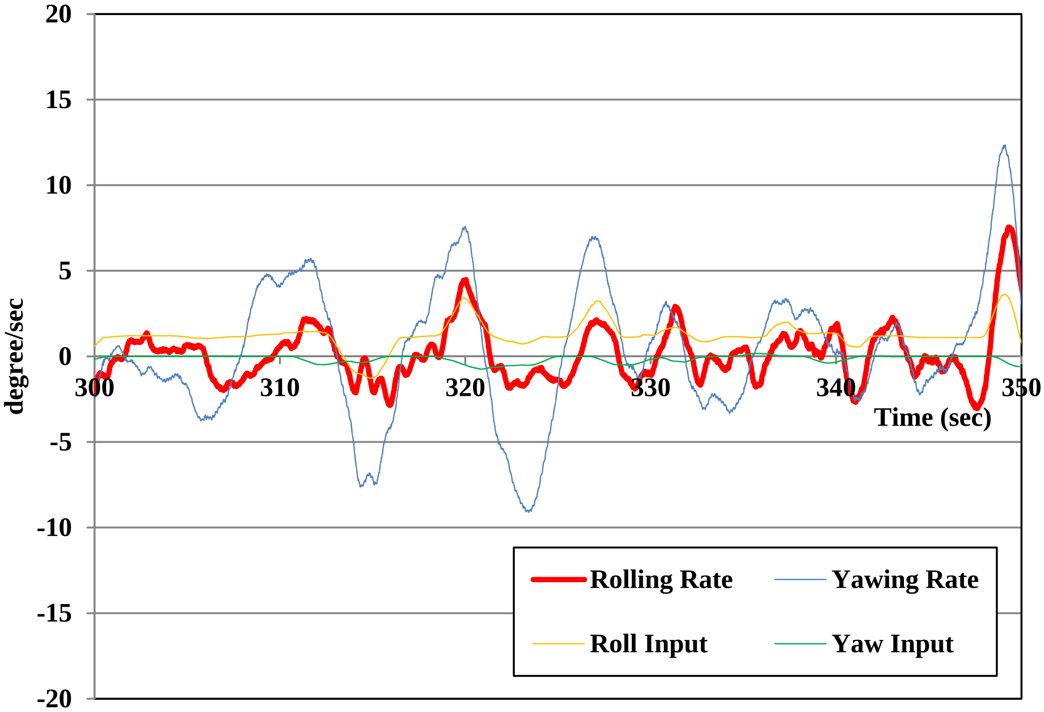

Figure 13: Graph of the rolling and yawing motion (initial)

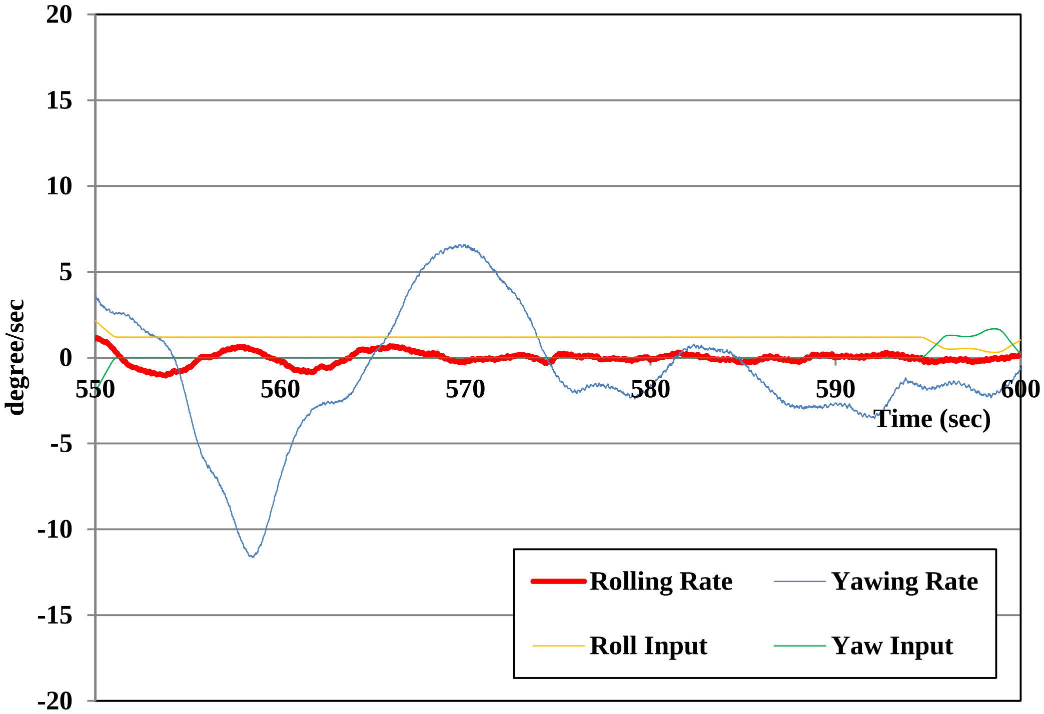

Figure 14: Graph of the rolling and yawing motion (stable)

5. Conclusions

Figure 15: Stable hover flight of cyclocopter

The present paper describes design and development of 100kg class UAV cyclocopter. The new concept of control mechanism was adopted, and rotor design parameters were determined through CFD analysis. The control mechanism became perfect axisymmetric and accurate compared to the previous system. Figure 15 shows stable flight test of cyclocopter at tethered condition. A stable hovering flight could be demonstrated without any strings; however, it wasn't performed due to safety reasons especially at 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 used as a UAV system once a larger engine is equipped.

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