Thrust Control Mechanism of VTOL UAV Cyclocopter with Cycloidal Blades System

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ABSTRACT: This study describes the control mechanism of a VTOL UAV cyclocopter. The cycloidal blades system (CBS), which is a thrust system of cyclocopter is composed of several blades rotating about a horizontal axis. To generate the required thrust, the pitch angles of the blades are periodically oscillated by a pitch control mechanism. And it can change both the magnitude and the direction of the thrust almost instantly. For the thrust control mechanism of the cyclocopter, the mathematical model is derived, and the control forces to control the magnitude and direction of the thrust are determined. In addition, it is designed and developed by radio-controlled actuators.

Key Words: cycloidal blades system, cyclocopter, control mechanism, VTOL, UAV.

INTRODUCTION

THE cycloidal blades system (CBS) is a thrust system that consists of several blades rotating about a horizontal axis perpendicular to the direction of normal flight (Foshag and Boehler, 1969). To generate the thrust required, the pitch angles of the individual blades to the tangent of the circle of the blade's path are varied by a pitch control mechanism installed in the CBS, designed such that the periodic oscillation of the blades about their span axis may be changed in both amplitude and phase angle. Therefore, the CBS is able to vector its thrust anywhere perpendicular to the rotating axis. This characteristic enables the CBS to vertically take off and land, hover and fly forward by the simple adjustment of blade pitch angles. Figure 1 shows a typical pitch motion experienced by a blade on its rotating orbit. The blade on the top and the bottom positions produces upward force with a positive angle of attack. On the other hand, the blade on the left and the right positions produces a small amount of force, because the blade has little angle of attack.

In the 1920s, Kirsten at the University of Washington became interested in cycloidal propulsion (Kirsten, 1928, 1935). He built and tested a cycloidal rotor with a π pitch cycloidal blade motion in the wind tunnel to investigate the possibilities of application of cycloidal rotor to airship, aircraft, and vessel. Eastman succeeding Kirsten examined the high pitch cycloidal rotor to utilize it in the forward flight. At the same time, NACA started investigating at Langley Field, Virginia, the fundamental claims of the cyclocopter as a VTOL aircraft. This work was done by Wheatley in the 1930s (Wheatley, 1933; Wheatley and Windler, 1935). He investigated the performance of a cycloidal rotor with low pitch blade motion through the simple analytical approach and wind tunnel tests. In recent years, Bosch aerospace re-investigated the cycloidal rotor (not studied for 50 years) to apply it to the lighter-than-air vehicle to give positive control of an airship during hover, take-offs, and landings (Gibbens and Boschma, 1999). In the test for six-bladed cycloidal rotor with each blade having a chord of 1 ft and a span of 2 ft, performance approaches 11 lb/HP, which is quite a high value compared to the conventional screw propeller.

In this article, the thrust control mechanism of CBS for a VTOL UAV cyclocopter is described. Figure 2 shows a cyclocopter which is developed to evaluate the potential of CBS for a VTOL vehicle. It is 46 kg and equipped with a 16 HP engine (Yun, 2004; Yun et al., 2004).

SINUSOIDAL LOW PITCH SYSTEM

The thrust control mechanism of the sinusoidal low pitch system is shown in Figure 3. It comprises the point of eccentricity P and the control rod which connects the point of eccentricity to the point on the chord line

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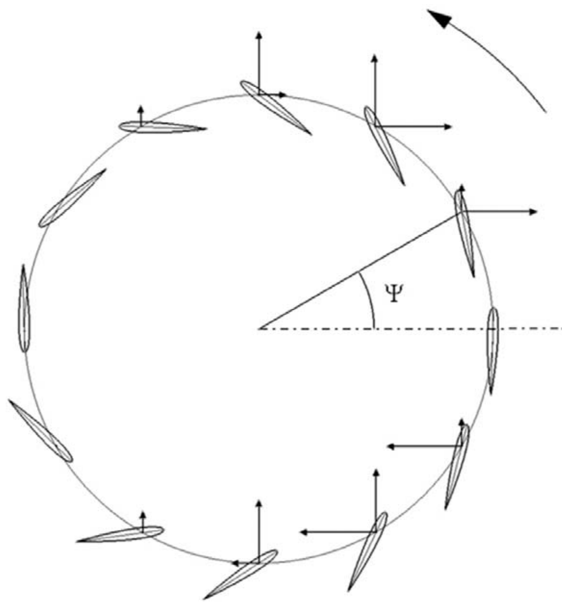

Figure 1. *Blade pitch angle variation during a revolution.*

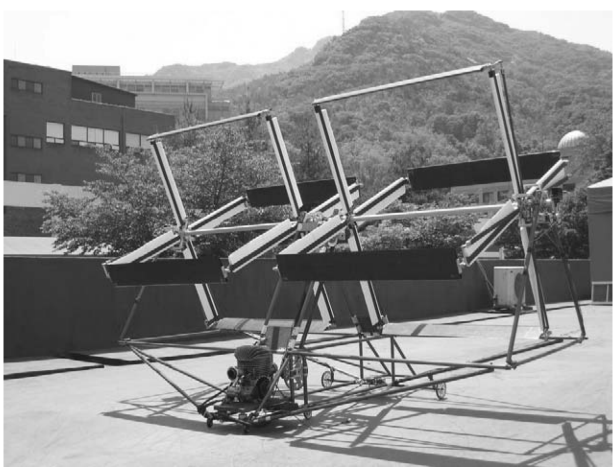

Figure 2. *Developed cyclocopter.*

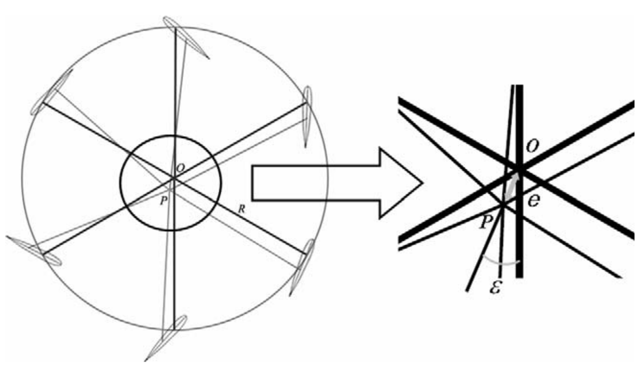

Figure 3. *Sinusoidal low pitch system.*

of a blade, grossly. The principle of thrust control of cycloidal rotor is that when P is located in an arbitrary position which is away from the rotor center O, the instantaneous pitch angle θ which is the angle between

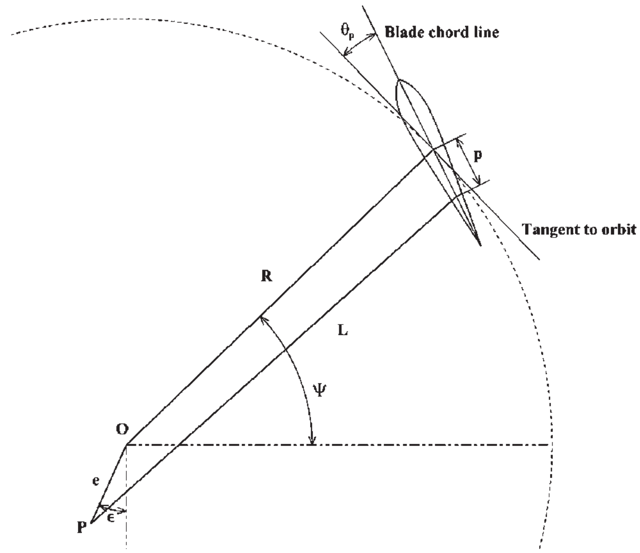

Figure 4. *Geometry for the blade pitch and eccentricity.*

the chord line and the tangential line of a blade path is generated by the control rod connecting P to O, and θ can be varying with respect to the azimuth according to a rotation of a blade. Therefore, if the position of P is adjusted, the magnitude and the direction of thrust can be controlled. The position of P can be described in a polar coordinate system. The radial coordinate and the angular coordinate is presented by the magnitude of eccentricity e and the phase angle of eccentricity ε. The magnitude of eccentricity e is defined as the distance from the center of rotation O to the point of eccentricity P and the phase angle of eccentricity ε is defined as the angle between the line OP and the vertical line. e and ε take charge of the magnitude of the thrust and the direction of the thrust vector, respectively and each variable is analogous to the collective pitch and the cyclic pitch of the thrust control of a helicopter.

Referring to Figure 4, the pitch angle in the sinusoidal low pitch system in terms of magnitude, phase angle, and azimuth angle is written as:

$$\theta = \frac{\pi}{2} - \cos^{-1}\left(\frac{a^2 - L^2 + p^2}{2ap}\right) - \sin^{-1}\left(\frac{e}{a}\cos(\Psi + \varepsilon)\right) \quad (1)$$

where a is the distance from the eccentricity to the pivot point of a blade given by $a = \sqrt{e^2 + R^2 + 2eR\sin(\Psi + \varepsilon)}$ and p is the distance from the pivot point to the connection point between a control rod and the blade, and L is the length of the control rod.

The pitch angle variation of each blade in the low pitch system according to azimuth angle is shown in Figure 5. The phase angle and the magnitude of the eccentricity are set to be zero and $0.05R$, respectively. The pitch angle variation is similar to the sine curve. Therefore this low pitch system is called the sinusoidal low pitch system. Since the pitch angle is varied like sine

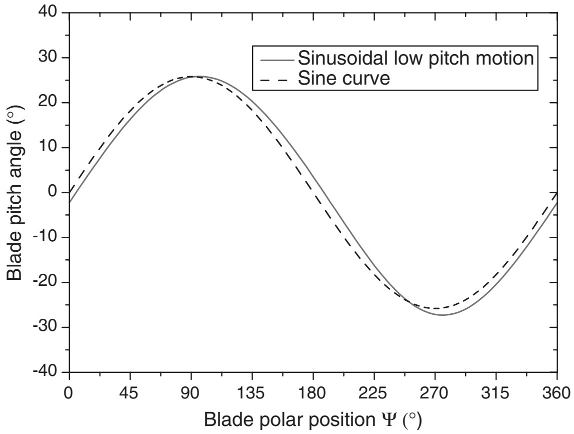

Figure 5. *Pitch angle variation w.r.t. azimuth angle.*

curve, the pitch angle will be assumed to be a sinusoidal function of Ψ, and the instantaneous pitch angle θ can be expressed as:

$$\theta = \theta_a \sin(\psi + \varepsilon) \tag{2}$$

where θ_a is the amplitude of the pitch angle for varying angles. The above equation may be used to calculate the aerodynamic loads for CBS.

MATHEMATICAL MODELING OF THRUST CONTROL MECHANISM

The control force must be determined to give the blades cyclic pitch motion. A motion of the control link changes the pitch of the blades as they rotate. Therefore, in cycloidal rotor, all control forces must arise from pitching moments on the blades. In this section, the control force is calculated to change the pitch angle of blades cyclically and the force loaded on the control rods is found.

Figure 6 represents the blade and control rod unit with magnitude and phase angle of eccentricity when the blade is at the azimuth angle, Ψ. The master control rod is used to analyze the unit control system because the master rod is mainly loaded. In the figure, point O is the center of rotation and R the radius of the rotor. The X–Y coordinate is fixed as the global coordinate system with origin P and X'–Y' coordinate is the local coordinate system rotating with the rotor. F_c is the individual control force causing the blade to oscillate the pitch angle. Aerodynamic forces and the centrifugal force of the blades generate the moment about the blade pivot point, and the blade pitching motion is induced by the control force of the rod. Therefore, the equation of motion for the blade about the feathering axis becomes

$$M_{B_a} + M_{B_c} + M_C = I_{B_p}\ddot{\theta}_P \tag{3}$$

where M_{B_a} is the moment about the blade pivot point due to aerodynamic forces on the blade, M_{B_c} the moment about the pivot point due to the centrifugal forces of the blade, M_C the moment arising from the control rod, and I_{B_p} the blade's mass moment of inertia about the pivot point. The moments can be obtained from the geometrical relations in Figure 7.

$$M_{B_a} = qC_L SP_a \cos\theta_p + qC_D SP_a \sin\theta_p \tag{4}$$

where q is the dynamic pressure, C_L the lift coefficient, C_D the drag coefficient, and S the projected area of the blade.

$$M_{B_c} = F_{B_c} \times h = m_b\omega^2 P_m R\cos\theta_p \tag{5}$$

where F_{B_c} is the centrifugal force of the blade and $\omega = \dot{\Psi}$, the frequency of the rotating rotor.

$$h = \frac{P_m R\cos\theta_p}{b} \tag{6}$$

$$b = \sqrt{P_m^2 + R^2 + 2P_m R\sin\theta_p} \tag{7}$$

$$M_C = \left\{F_{CX'}\sin\left(\beta - \frac{\pi}{2}\right) + F_{CY'}\cos\left(\beta - \frac{\pi}{2}\right)\right\}P_c \tag{8}$$

where β is the angle between the control rod and the blade chord and P_c is the distance between blade pivot point B and the pitch horn attachment point C. $F_{CX'}$ and $F_{CY'}$ are the control forces in the X′-direction and in the Y′-direction, respectively.

$$F_{CX'} = \frac{I_{R_{center}} \times \phi'' - M_{C_{Drag}}}{L} \tag{9}$$

$$\beta = \cos^{-1}\left(\frac{L^2 + P_c^2 - a^2}{2LP_c}\right) \tag{10}$$

$$\phi = \frac{\pi}{2} + \theta_p - \beta \tag{11}$$

where ϕ is the angle between R and L, $I_{R_{center}}$ is the mass moment of inertia of the control rod about the control center, and $M_{C_{Drag}}$ the generated moment by drag on the rotating control rod. Now, to find the force applied on the eccentricity point of the control rod along the Y′-direction, the control rods are considered. The control rods are also subjected to centrifugal loadings since they rotate with blades. The centrifugal force at the root of the control rod is given by:

$$F_R = m_R l(\dot{\Psi} + \dot{\varphi})^2 \tag{12}$$

where m_R is the mass of the control rod and $\dot{\varphi}$ the angle between hub arm and control rod. Therefore, the force on the eccentricity point is given by:

$$F_{CY'}|_{root} = F_{CY'} + F_R \tag{13}$$

This force is expressed in the rotating coordinate system. If the force in the rotating coordinate system is

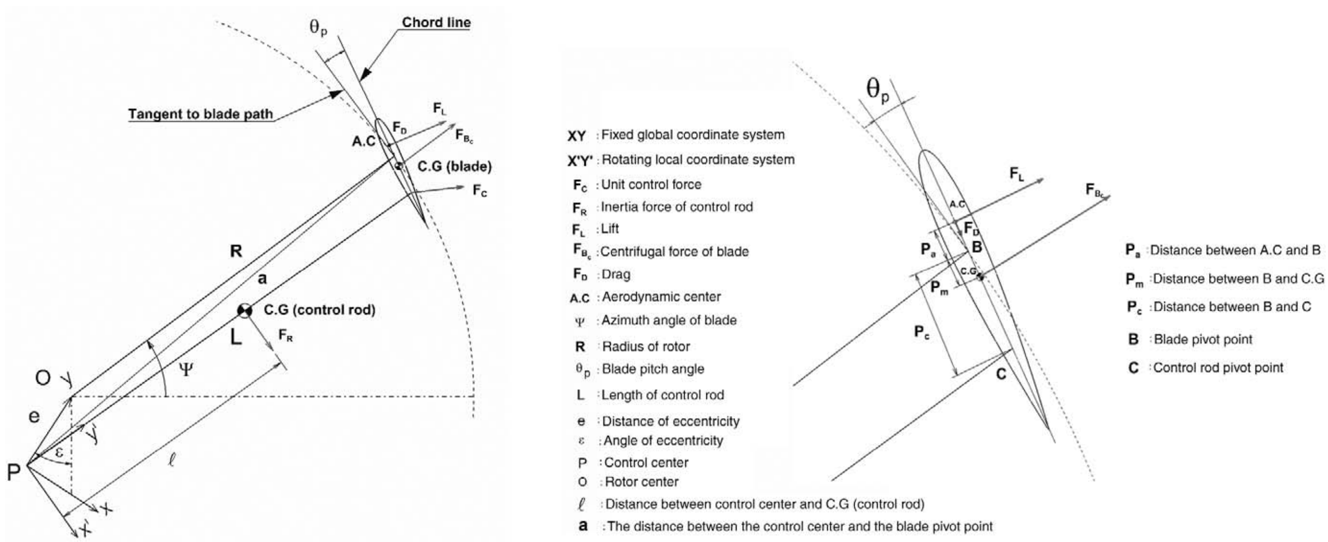

Figure 6. Geometry and forces of control unit.

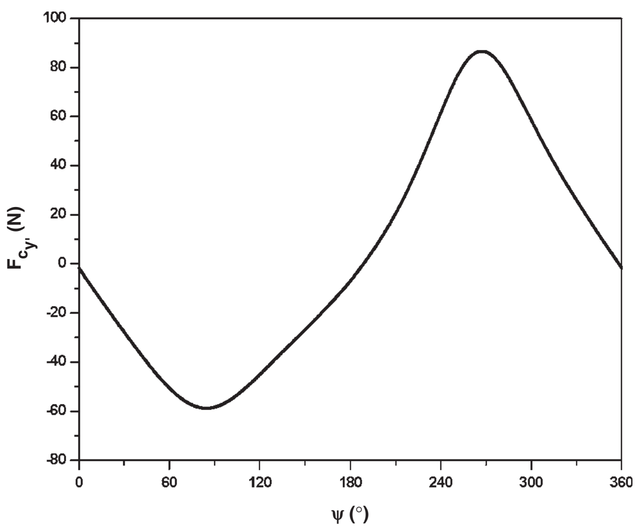

Figure 7. Force acted on the tip of a control rod.

transformed into non-rotating fixed system, the forces are as follows:

$$F_{\mathrm{CX}} = F_{\mathrm{CY}'}|_{\mathrm{root}} \sin\tau, \quad F_{\mathrm{CY}} = F_{\mathrm{CY}'}|_{\mathrm{root}} \cos\tau \tag{14}$$

where τ is the angle between the control rod and line OP. The total control force and torque required for the thrust control of the CBS rotor is obtained by summing up individual control forces of the control rod acting on the eccentricity point. The required control force to control the magnitude of thrust becomes

$$F_{\mathrm{TM}} = \sum_{i=1}^{N_{\mathrm{b}}} F_{\mathrm{CY},i} \tag{15}$$

and the control force to control the direction of thrust vector is

$$F_{\mathrm{TP}} = \sum_{i=1}^{N_{\mathrm{b}}} F_{\mathrm{CX},i} \tag{16}$$

where N_{b} is the number of blades. Therefore, the required control torque for direction change of the thrust vector is given by

$$Q_{\varepsilon} = e \times F_{\mathrm{TP}} \tag{17}$$

CONTROL FORCES FOR THRUST CONTROL OF UAV CYCLOCOPTER

The design parameters of the thrust control mechanism for UAV cyclocopter, such as the capacity of DC servos and the geometry and material of the control rod, can be determined by applying the mathematical model of the control system to the specified CBS rotor for UAV cyclocopter. The control forces can be divided into the control force for magnitude of thrust and the control force for direction of thrust. The process of determination of control force is as follows. The force acted on the control center by rotating CBS rotor is divided into the component of the direction of line OP and the perpendicular component of the direction of line OP, and each directional force is obtained with respect to the azimuth. The criterion of the thrust control force of the CBS rotor is the maximum force acted on the control center by rotating rotor. Hence, the maximum force among forces obtained with respect to the azimuth, may be the minimum necessary control force.

The component of the direction of line OP is the control force to control the magnitude of thrust and the perpendicular component of the direction of line OP is the control force to control the phase angle of the thrust vector. However, the control force to control the direction of the thrust vector is converted into control torque which multiplies the control force for thrust direction by the magnitude of eccentricity, because the control of thrust direction is done by a rotating mechanism. Table 1 shows running conditions for analysis. Figure 7 shows the variation of axial force applied to a control rod at a point pivoted to a blade in the unit control system. When a control rod is located at the upper side of the CBS rotor, the load applied to the control rod is compressible. Reversely, when a control rod is located at the lower side of the CBS rotor, the control rod is under tension loading state. Figure 8 shows the variation of axial force of the control rod at the point clamped to on the rotating control plate. Differently from the tip, a control rod is under tension loading state at all positions, because the centrifugal force of a control rod is generated during rotation. Figure 9 shows the applied control force at the eccentricity point in the longitudinal direction over the range of $0^\circ \leq \Psi \leq 90^\circ$. Maximum force occurs at about $\Psi = 0^\circ$ and $\Psi = 90^\circ$ with a value of 85 N. A negative means that the force is acted along the vector $\overrightarrow{OP}$. Figure 10 shows the applied control torque at the control block with respect to the azimuth angle. It can be seen that the minimum torque applied by servo motor at the control block is about 12 kg cm. Therefore, the servo motors and servo linkages system must be selected and designed to be operated under the action of control force and torque.

Table 1. *Specifications of UAV cyclocopter.*

Parameter	Value
Radius of rotor	0.7 (m)
Number of blades	4
Airfoil	NACA0012
Span	1 (m)
Chord	0.15 (m)
Mass of a blade	0.4 (kg)
Rotating speed	600 (rpm)
Blade pivot point	47%
Aerodynamic center	25%
Control rod pivot point	97.3%
Center of gravity of a blade	47%
Mass of a control rod	0.1 (kg)
Profile of a control rod	$5.5 \times 25 \times 670$ (mm^3)
Maximum pitch angle of a blade	32 (°)
Amplitude of eccentricity	50 (mm)
Phase angle of eccentricity	0 (°)

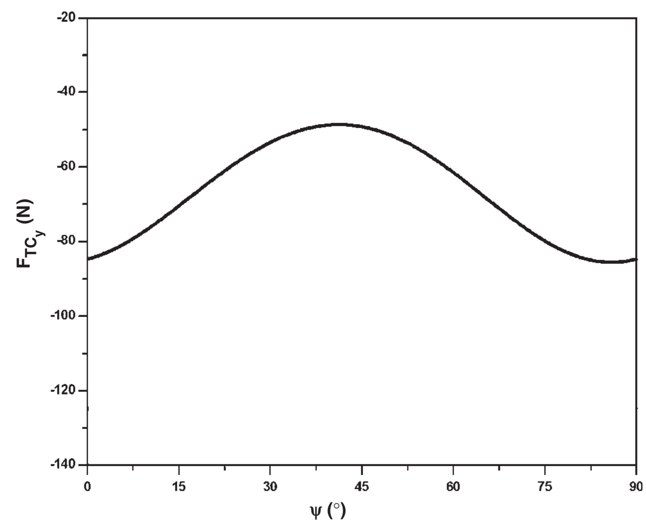

Figure 9. *Control force of the magnitude of thrust.*

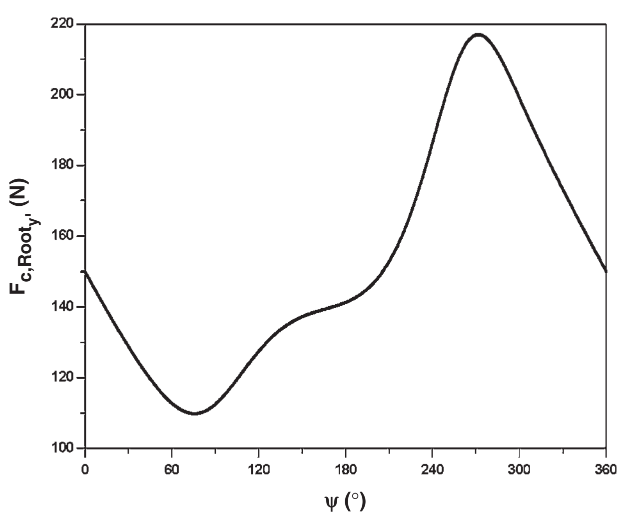

Figure 8. *Force acted on the root of a control rod.*

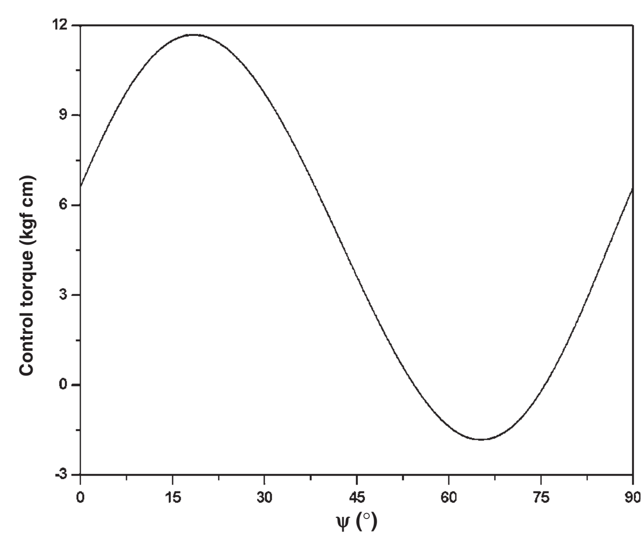

Figure 10. *Control torque of the direction of thrust.*

DESIGN AND REALIZATION OF THRUST CONTROL MECHANISM

For isolating the control block from the vibration of the blade, screw–nut mechanism is used for the control system for cycloidal rotor. Figure 11 shows a schematic drawing of the control system. Figure 12 shows that DC servo operates to change the magnitude of thrust. The small DC servo in the right-center position in the figure moves the slide variable resistance, and then the upper large DC servo which is coupled on the slide variable resistance rotates the screw guide through the belt. The rotation of this screw guide makes the up and down movement of the sliding nut. This movement changes the amplitude pitch angle of blades, and therefore the magnitude of thrust changes. Figure 13 shows that DC servo operates to change the direction of thrust. Lower DC servos, which connected to the main shaft, rotate the whole control block through the belt. Then the direction of thrust varies by this rotation. Figure 14 shows an assembled control system of UAV cyclocopter using radio-controlled actuators.

CONCLUSIONS

In this study, the control mechanism of a UAV cyclocopter is described for hovering and low speed forward flight. The control of magnitude and direction of

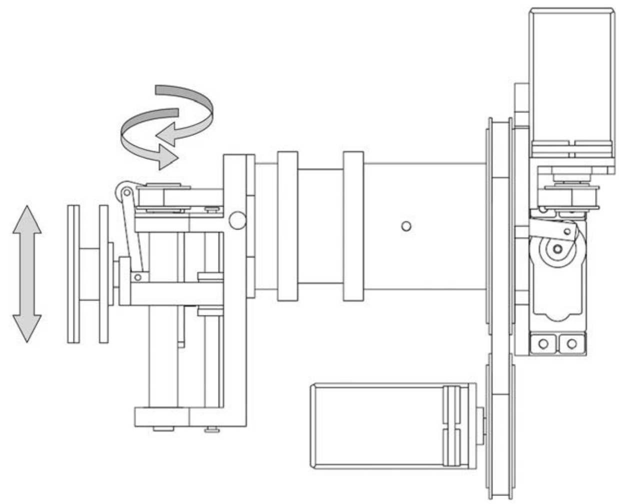

Figure 12. Servo operation to control the magnitude of thrust.

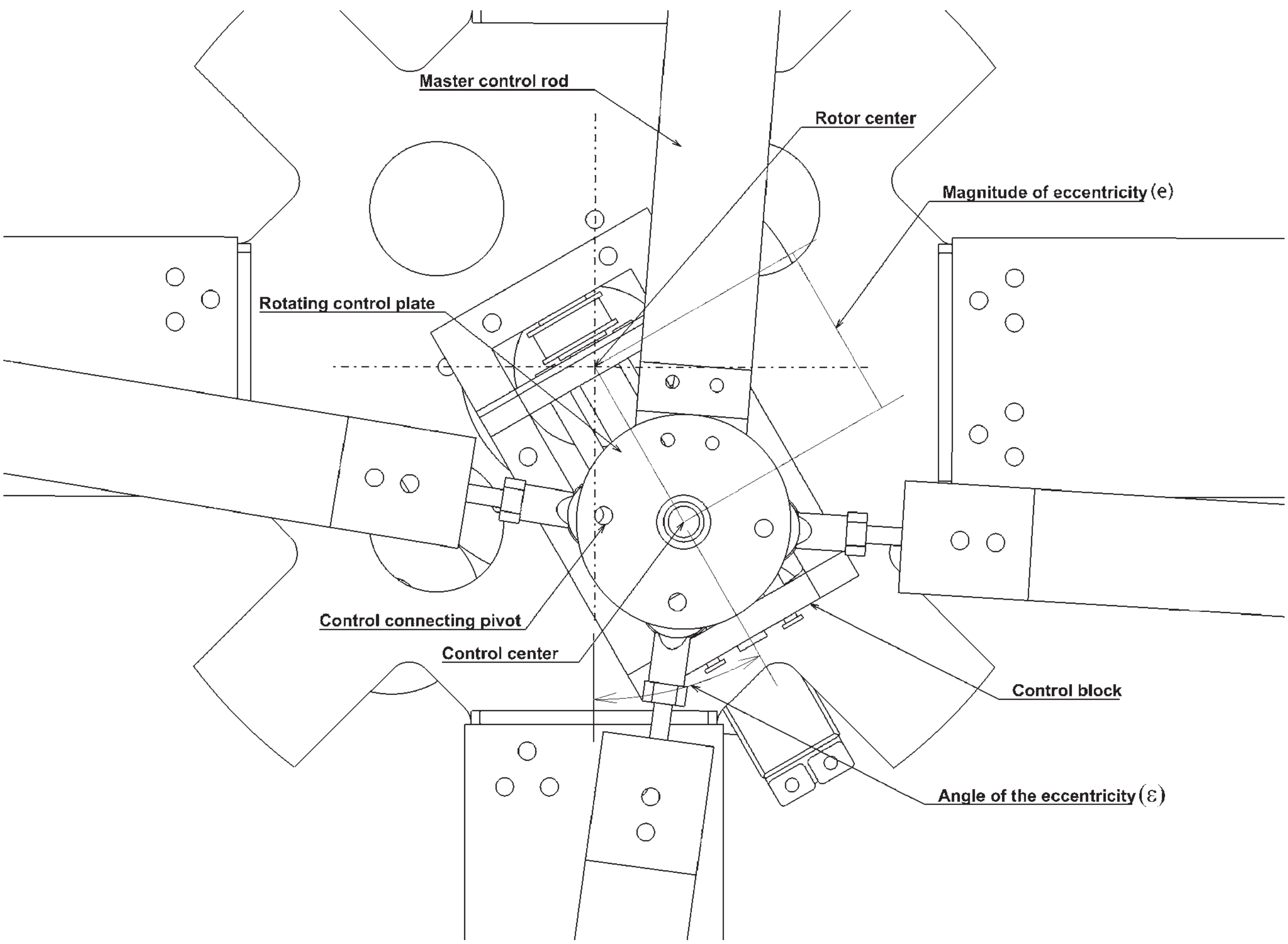

Figure 11. Configuration of the thrust control mechanism.

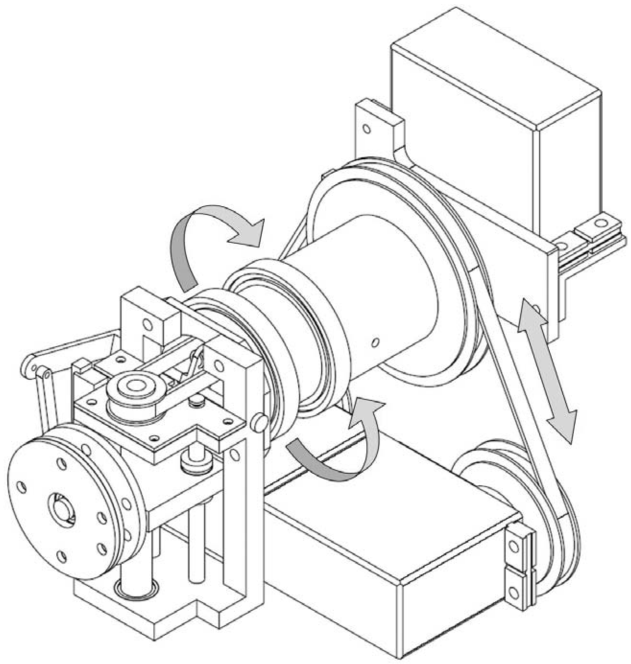

Figure 13. *Servo operation to control the direction of thrust.*

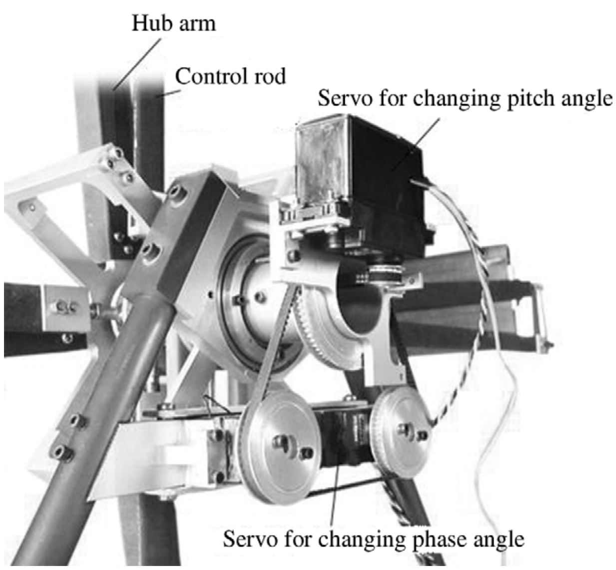

Figure 14. *Assembled control system.*

thrust produced by a cycloidal rotor can be done by a control block motion in a translation manner, thereby changing the magnitude of the rotor thrust, or in a rotation manner, thereby changing the phasing of the aerodynamic loads. The pitch angle is varied like a sine curve with respect to the azimuth angle. The mathematical model for sinusoidal low pitch system is induced, and the control force for thrust control of UAV cyclocopter can be obtained. From this result, radio-controlled actuators that generate the control force can be determined to be appropriate for the control force.

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