Total Energy Control System Design for Longitudinal Dynamics of Complex Articulated Ornithopter

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ABSTRACT

This paper describes the design of total energy control system(TECS) for longitudinal flight of a complex articulated ornithopter. Aerodynamic coefficients are acquired with an analysis tool based on the Vortex Lattice Method. Equations of motion reflecting the flapping-wing effect are designed, and available control inputs are selected. A flight controller using these control inputs is designed, and simulation results are analyzed.

1 Introduction

TECS controls aircraft's thrust and pitch angle based on the total energy demand and the total energy distribution error calculated by flight altitude and speed. The thrust command equals the total energy to the desired total energy, and the pitch angle command reduces distribution error of the kinetic and the potential energy. In general fixed-wing aircraft, the propulsion equipment and the elevator are operated by the thrust and pitch angle command. A. A. Lambregts introduced autopilot using this principle [1].

Jang and Han analyzed the PX4 project, that is an open platform of the autopilot hardware and software for developing drones [2]. This platform is popular and used in many research institutes because of its compatibility with various aircraft. The TECS principle is used in the PX4 to control fixed-wing aircraft. So, using this principle can help the improvement of accessibility to develop an ornithopter system.

The ornithopter does not have propulsion equipment and generates thrust and lift by flapping the wing. To control this system, many research about the analysis of flapping-wing effects have been conducted. D. Kumar *et al.* did a wind tunnel experiment to analyze the flapping frequency and stroke-ratio effects of a single articulated ornithopter [3]. And Wolfgang Send *et al.* analyzed active wing twist control effects of a complex articulated ornithopter [4].

This paper contains research about the longitudinal simulator design of the complex articulated ornithopter. First, available control inputs are selected, and their effects are considered. Then, desired flight altitude and speed are set, and the TECS controller is designed with the selected control inputs. Finally, the simulation results are analyzed.

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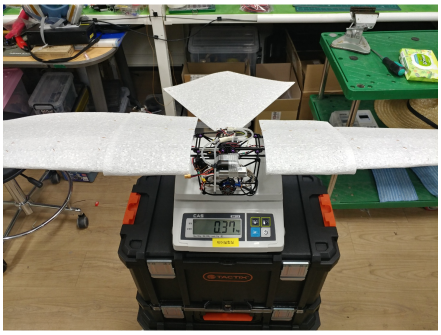
2 Equations of motion modeling

2.1 Aerodynamic analysis

Chungnam National University has researched the articulated ornithopter system. Kim *et al.* designed and fabricated a complex articulated ornithopter named USGull-mini, and did flight test in 2018 [5]. The research continues recently, and USGull-mini flight performance improvements have been carried out. The specification is shown in Table 1.



Wing span	1,450 mm
Weight	370 g
Max. flapping frequency	4 Hz

Table 1: USGull-mini specification

The inner and outer wing folding angles are changed according to the flapping-motion affecting the aerodynamic coefficients change. Both wing's folding angles should be considered separately in the complex articulated structure unlike the single articulated. The flapping-wing motion states can be divided into 12 steps based on each wing's folding angle increase/decrease occurrence as shown in Figure 1.

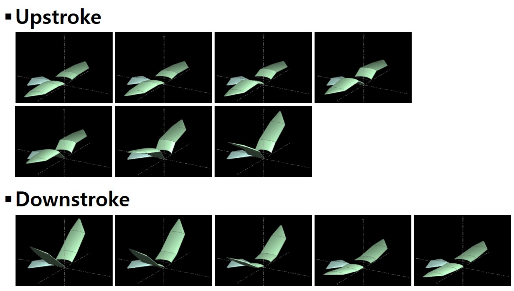


Figure 1: The flapping-wing motion of USGull-mini

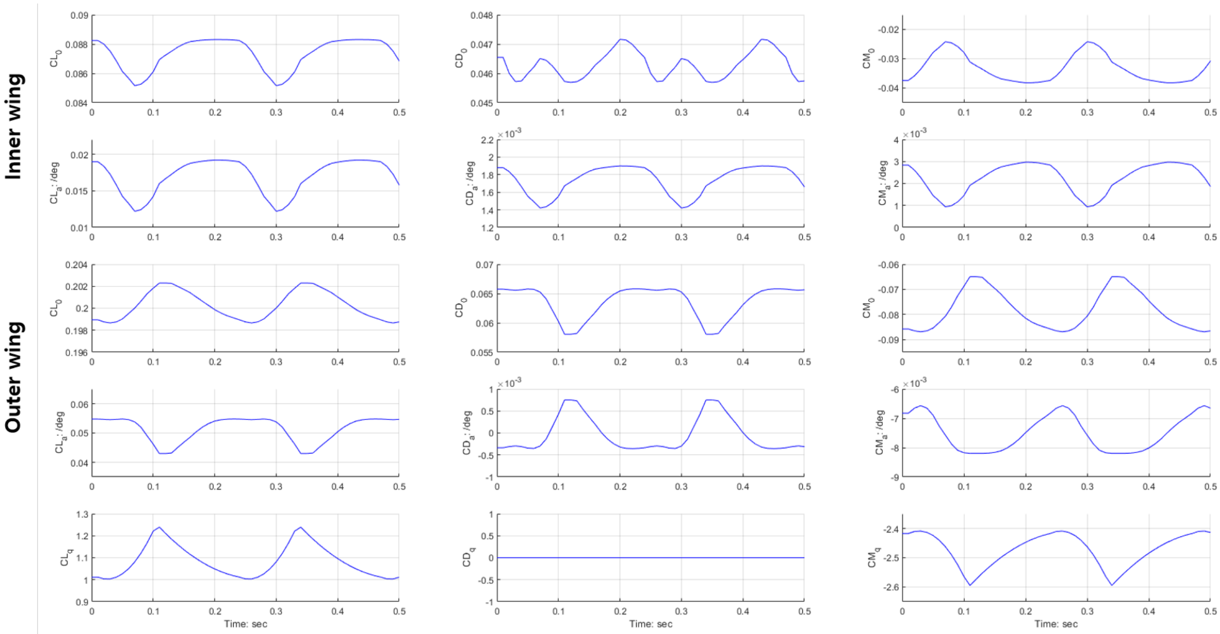


Figure 2: Aerodynamic coefficient change for two periods of flapping motion

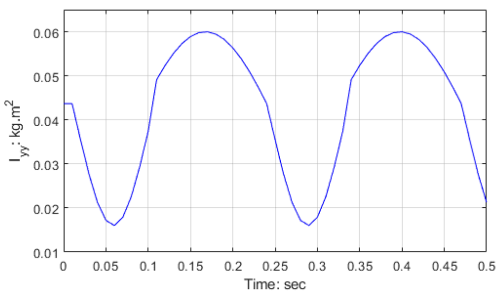


Figure 3: Moment of inertia change for two periods of flapping motion

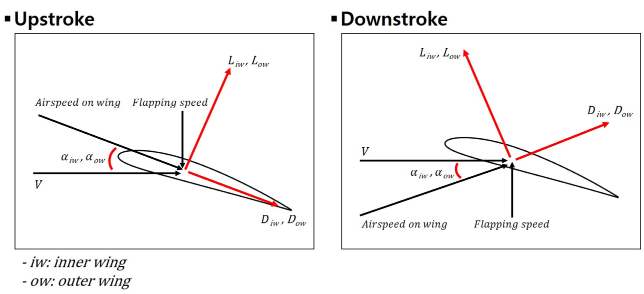


Figure 4: Lift and drag geometry during upstroke and downstroke

XFLR5 is an analysis tool based on the Vortex Lattice Method (VLM) suitable for aircraft at low Reynolds number. HUA Zhao-min *et al.* used XFLR5 to compare aerodynamic efficiencies of two-section and three-section flapping-wing mechanism [6]. This research showed that XFLR5 can analyze the articulated ornithopter. The lift, drag, and moment coefficients are acquired by its aerodynamic analysis. Figure 2 represents the flapping effects on the coefficients at a condition of flapping frequency 4Hz. In addition to the aerodynamic coefficient, the moment of inertia changes according to the flapping-motion, as shown in Figure 3.

2.2 *Equations of motion modeling*

Flapping-wing motion generates an airspeed along the z-axis of the aircraft, and it causes the angle of attack change on the wings. As a result, the lift's x-axis component is replaced by thrust. Figure 4 represents these effects, and it is needed to design equations of motion. The equations of motion related with the longitudinal axis are given in equation (1)-(4).

$$\begin{aligned}\dot{V} = (&L_{iw}sin\alpha_{iw} - D_{iw}cos\alpha_{iw} + L_{ow}sin\alpha_{ow} \\ &- D_{ow}cos\alpha_{ow} - D_{tw} - D_q - mgsin\gamma)/m\end{aligned} \tag{1}$$

$$\begin{aligned}\dot{\alpha} = &(-L_{iw}cos\alpha_{iw} - D_{iw}sin\alpha_{iw})/(mV_{iw}) \\ &+ (-L_{ow}cos\alpha_{ow} - D_{ow}sin\alpha_{ow})/(mV_{ow}) \\ &+ (-L_{tw} - L_q + mgcos\gamma)/(mV) + q\end{aligned} \tag{2}$$

$$\dot{q} = (M_{iw} + M_{ow} + M_{tw} + M_q)/I_{yy} \tag{3}$$

$$\dot{\theta} = q \tag{4}$$

where $L = \bar{q}SC_L$, $D = \bar{q}SC_D$, and $M = \bar{q}ScC_M$. L and D denote lift and drag forces, M is pitch moment. And V is the airspeed, α is the angle of attack. q is the pitch rate and θ is the pitch angle. γ and g are flight path angle and gravity constant. m, S, c, and I_{yy} are physical properties representing the mass, the wing surface, the mean chord length, and the moment of inertia. iw, ow, and tw are abbreviations meaning inner wing, outer wing, and tail wing. And $\overline{q}$ is the dynamic pressure. Finally, C_L, C_D, and C_M are the aerodynamic coefficients of lift, drag, and pitch moment.

3 TOTAL ENERGY CONTROL SYSTEM DESIGN

3.1 Control input analysis

A simulation for control input analysis is configured and its contents are as follows. The aircraft takes off from the ground and climbs to an altitude of 30 m. After reaching the desired altitude, the aircraft cruises maintaining it. There is no desired flight speed, but it has the limitation of plus/minus 20 ° in the pitch angle command. Flapping frequency, stroke-ratio, and active wing twist angle control are selected as control input candidates. Stroke-ratio is expressed as downstroke speed divided by upstroke speed, and active wing twist angle is controlled by an additional actuator mounted on the wingtip. The thrust and lift effects from flapping-motion according to the changes of these candidates are shown in Figure 5.

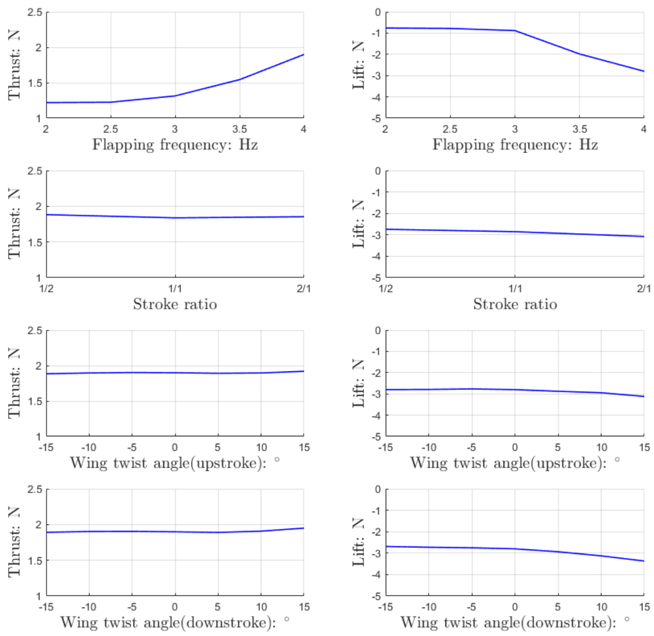


Figure 5: Control input effects

Each control input's effects are as follows. The increase in flapping frequency causes an increase in the thrust and a decrease in the lift. And the decrease in stroke-ratio causes an increase in the thrust and the lift. Finally, the increase in wing twist angle in the upstroke state causes an increase in the thrust and a decrease in the lift, but the increase in the thrust is negligible, and the same trends are displayed in the downstroke state. These analysis results are used to design the TECS controller.

3.2 Total energy control system design

TECS controller consists of two loops, total energy control and total energy balance control. The total energy control is based on the equation expressed as the kinetic and the potential energy sum. And the total energy balance control is based on the equation expressed as the difference between the kinetic and the potential energy. It is represented as follows.

$$E_T = \frac{1}{2}mV^2 + mgh \tag{5}$$

where E_T is the total energy, the energy rate can be derived as:

$$\dot{E}_T = mV\dot{V} + mg\dot{h}. \tag{6}$$

The energy balance E_B and the energy balance rate $\dot{E}_B$ can be defined in the same way.

$$E_B = -\frac{1}{2}mV^2 + mgh \tag{7}$$

$$\dot{E}_B = -mV\dot{V} + mg\dot{h} \tag{8}$$

The TECS controller determines thrust command using the total energy control loop and pitch angle command using the total energy balance control loop. In general fixed-wing aircraft, the thrust and pitch angle command affect propulsion equipment and elevator operations. The ornithopter also has an elevator, but it does not have propulsion equipment to generate thrust. So, the TECS controller should be modified to be suitable for this system, like the block diagram in Figure 7. The propulsion equipment control is replaced by flapping frequency and active wing twist angle control. Control concept representing the above is as follows.

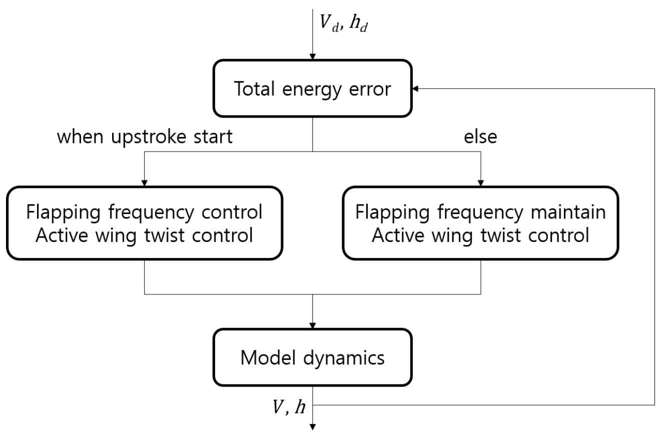


Figure 6: Total energy control loop concept

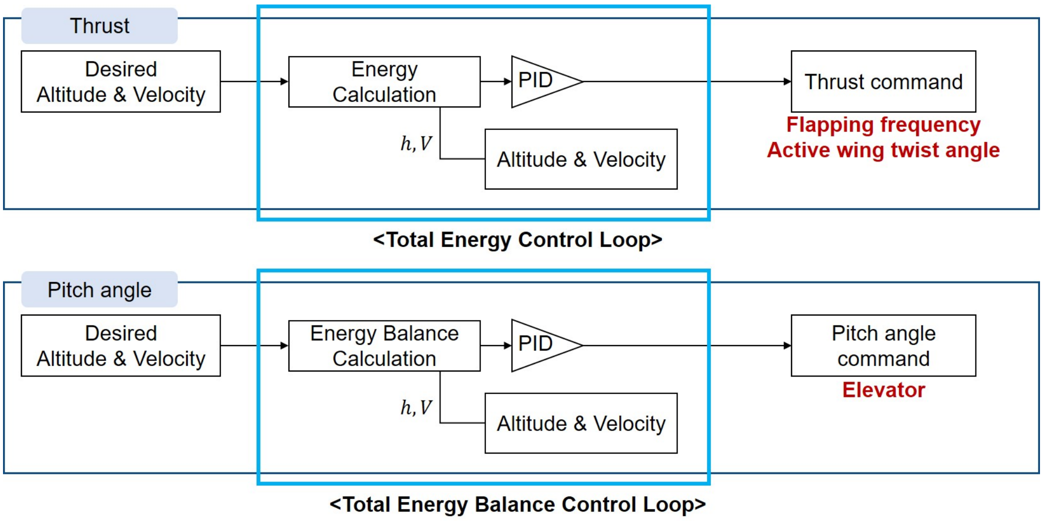


Figure 7: Modified TECS controller

The flapping frequency is controlled when the upstroke state starts, and maintained during that flapping-motion. The active wing twist angle is controlled in real-time. The flapping frequency increases to generate the thrust when the flight speed of the aircraft is lower than the desired flight speed, and the active wing angle decreases to compensate for the loss of the lift caused by the flapping frequency. On the other way, both control inputs operate in reverse of the way above when the flight speed of the aircraft is higher than the desired flight speed.

Stroke-ratio control is not used in the modified TECS controller. It's because both flapping frequency and stroke-ratio are controlled through the electric motor operation. In order to control two elements with only one electric motor, rapid rpm control is required. However, it lacks feasibility when applied to an actual aircraft, so the stroke-ratio is fixed to an optimal value.

4 Controller performance analysis

4.1 *Simulation configuration*

A simulation is configured to analyze the TECS controller design result, and its contents are as follows. The aircraft takes off from the ground at a speed of 6 m/s and climbs to an altitude of 30 m. After reaching the desired altitude, the aircraft cruises maintaining it. Desired flight speed is set to 6 m/s in the entire flight state, and the pitch angle command has the limitation of plus/minus 20 °. There is no disturbance, and the simulation time is set to 300 s.

4.2 *Controller performance analysis*

Figures 8-9 show the simulation results. The aircraft reaches the desired altitude at about 100 s and cruises maintaining it. The elevator controls the aircraft's pitch angle, and the flapping frequency and wing twist angle control the flight speed according to the command. Flapping frequency decreases as the aircraft reaches the desired altitude, and wing twist angle control occurs actively to reduce flight speed at the beginning of the cruise state. Vibrations due to flapping-motion are shown in all states.

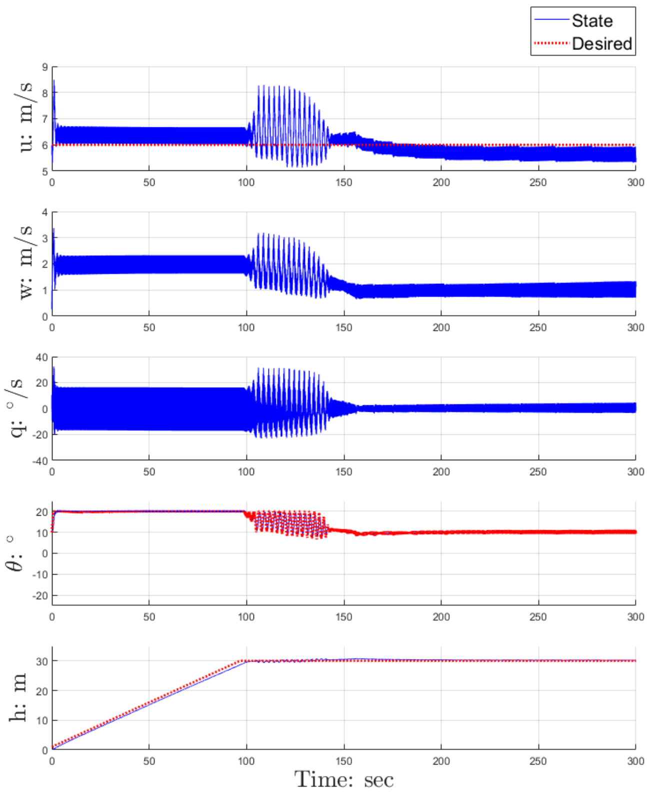


Figure 8: System states

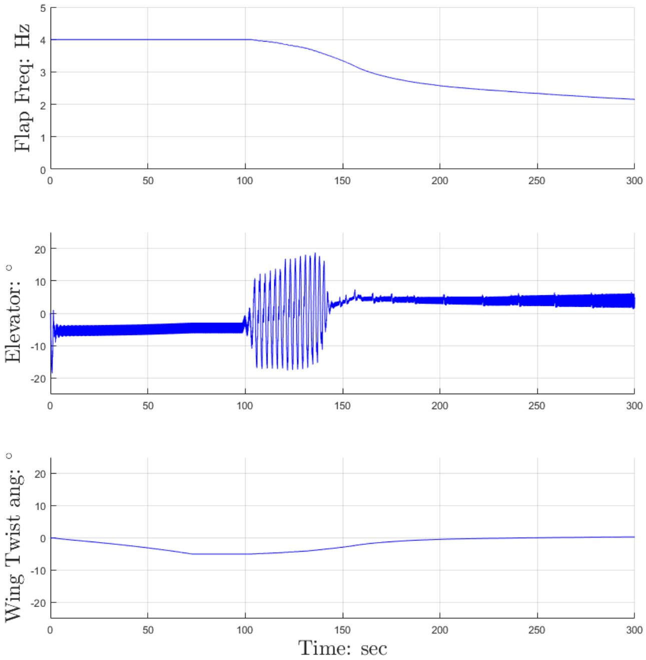


Figure 9: Control inputs

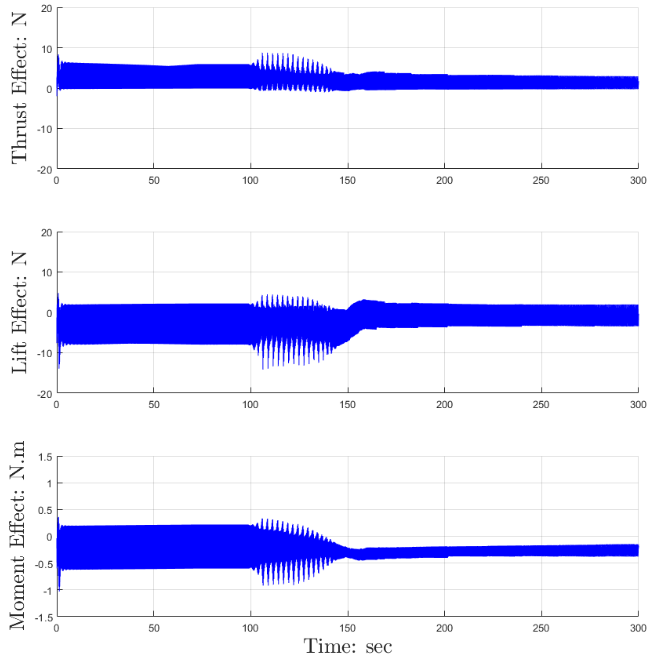


Figure 10: Flapping-motion effects

In the climb flight state, the target altitude is calculated in real-time, and in this state target altitude is higher than the current state. Because the total energy balance control loop controls elevator based on the difference between the kinetic energy and the potential energy, the current flight speed becomes higher than the desired speed. After the aircraft reaches the desired altitude and the cruise flight begins, the TECS controller reduces flight speed, but it has an error with the desired speed. TECS controller's control gain tunning is required to eliminate the error. However, this error is not decreased even with gain tunning for controllability improvement, and an increase in vibrations of system state occurs. So, the error increases contrary to what is intended.

Figure 10 represents the force and moment effects of flapping-motion. The thrust effect follows the trend of change in the flapping frequency, and the wing twist angle has some effects on it. The lift effect has a similar trend above, but with the opposite sign. Through this, it can be confirmed that the flapping frequency effect is greater than the active wing twist angle effect. The elevator affects the pitch moment, and it is confirmed that excessive operation of the elevator causes unstability on the entire force and moment effects through the simulation results for the period of 100 to 150 seconds.

5 CONCLUSION

In this paper, longitudinal dynamic modeling and controller were designed aimed at a complex articulated ornithopter. The aerodynamic coefficients and the moment of inertia that change according to the flapping-motion were derived, and the equations of motion reflecting the flapping-motion effects were designed. Control inputs for the ornithopter were selected and analyzed based on the analyzed dynamics. Flapping frequency and active wing twist angle control were selected as control inputs, and stroke-ratio was determined as the optimal value considering feasibility. A modified TECS controller was designed and applied taking into account the characteristics of the articulated ornithopter. A simulation for analyzing the designed controller was configured, and its control performances were analyzed with this. As a result, it was confirmed that precise control was difficult with only the TECS controller. Further research for precise control will be continued, and then research on optimal control for the ornithopter will be conducted in the future.

ACKNOWLEDGEMENTS

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