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Design, Fabrication, and Flight Test of Articulated Ornithopter

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Abstract

Recently, research on flapping wing aircraft is on the rise due to the weight reduction of sensors and actuators. However, studies on articulated ornithopter have been lacking and commercial articulated ornithopter is hard to find. In this paper, we design and fabricate an articulated ornithopter with flapping frequency of 2-3Hz and span of 1.8m. The design based on kinematic analysis is verified through Matlab and Solidworks, and Adams. The platform is made of carbon plate with EPP material skin. The design parameters are compared and verified using a motion capture camera. Additionally, this paper shows thrust analysis with respect to wing shapes sweptback and rectangular. Finally, the design parameters are verified and analyzed through a motion capture camera.

1 Introduction

The bird is an efficient and superior flying object with over 150 million years of evolution. Humans have longed to fly in the sky watching these birds. Leonardo da Vinci (1452 1519) first made wing flap wings, and in 1924 the mechanism for flapping wing aircraft was studied.[1] In 1930 Lippisch's early work was carried out and many attempts were made to imitate the flight of birds in a technical approach.[2] In the 1980s, the energy benefits of airflow with winged wings were studied.[3]
Recently, due to the weight reduction of the mounted equipment, interest in the winged flight robot is increasing. In 2015-2017, Chungnam national university, Korea, has carried out on system identification, route point flight, etc. using commercial winged robots of single articulated robots.[4] However, since a single articulated robot has a short span length, it requires a wing flap of 7 Hz or more in order to generate thrust and lift and is not suitable for energy saving effect.
On the other hand, the composite articulated winged robot can generate thrust and lift at the wing of 2-3 Hz because of its long span length. Also, real birds generate positive aerodynamics at downstroke and negative aerodynamics at upstroke. In the upstroke, the wing is folded to reduce the resistance and reduce the aerodynamic drag. By reducing inertia moment, the efficiency of flight can be increased.[5][6][7]
Smartbird, a complex articulated winging robot based on the shape of a gull, was developed by Festo in Germany in 2011. Smart bird is equipped with a servo on a wing tip to obtain a positive aerodynamic force by attaching a Hall sensor to the gear and using carbon plate and extruded polyurethane foam for weight saving. The specification of Smartbird is shown in Table 1.[8]

Figure 1: Smartbird

Span	2m
Weight	500g
Flapping Frequency	2-3Hz
Flight speed	4.7m/s

Table 1: Smartbird specification

Inspired by Smartbird, a few universities have been working on a complex articulated winging robot. In 2016, the Chinese graduate school of Harbin Institute of Technology conducted a composite articulated wing flapping kinematics study and analyzed it to make a flying body.[9] However, they did not analyze the design parameter and mechanism of the articulated winging robot using motion capture camera. In 2014, King Abdullah University of science and technology of Saudi Arabia conducted experiments on thrust and lift according to the wing shape. In this study, it was verified that the sweptback wing shape is larger in thrust and lift than the straight wing shape. However, this is the result of the UVLM simulation, which is not applied to the actual winging robot.[10]
In this paper, Chapter 2 describes an articulated winging robot is designed and fabricated through kinematic analysis. chapter 3 analyzes the design parameters are verified and analyzed

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through the motion capture camera. Chapter 4 analyzes the thrust according to the wing shape and area with a single axis load cell. Chapter 5 analyzes the flight test results.

2 Design and Fabrication of Ariticulated Ornithopter

This paper, designs and fabricats a 1.8m - class articulated wing-like body with a flap frequency of 2-3Hz based on kinematic equations. We verified it through Matlab and Solidworks, a 3D modeling tool, and Adams, a multibody dynamics simulation. The robot frame was made of carbon plate, and the skin was made of EPP material.[9]

2.1 Drive Mechanism Design

The articulated wing mechanism used in this paper was motivated by the Smartbird mechanism [8].
The power starts with a brushless motor and is transmitted to the main gear via the reduction gear. In order to operate in the frequency range of 2-3 Hz, the gear reduction ratio is designed as 44, which reduces the load on the motor. Main gear is connected to crank, coupler, and rocker (four-bar linkage) which transmit power to upper-spar and lower-spar, respectively.

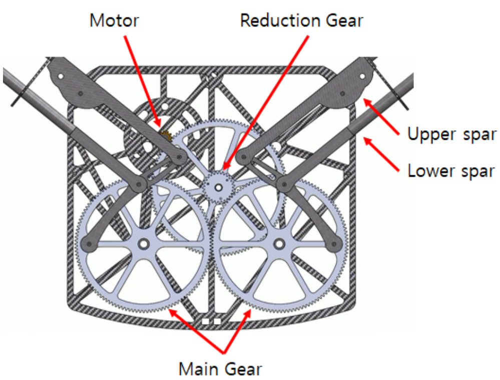

Figure 2: Drive mechanism

	Main Gear	Reduction Gear	Motor Gear
Teeth	120	27	12
Module	0.6	0.6	0.6
Diameter (mm)	73.2	17.4	8.4
Width (mm)	5	8	5

Table 2: Gear information

2.2 Main wing Design

The airfoil was modified in the same NACA7412 as the Smart bird. The wing mechanism of the articulated winged robot is similar to the human arm [11]. It is divided into three parts : the shoulder joint, the elbow joint and the wrist joint. The shoulder joint is divided into an upper-spar and a lower-spar. The upper-spar generates flapping motion, and the lower-spar produces translational motion. This motion of the shoulder joint is transferred to the elbow joint.
An elbow joint causes folding of the outer wing.[12] In order to generate thrust and lift positively, the wrist joint is in the upstroke state and the airfoil of the outer wing is in the pitch up state. In the downstroke, the airfoil of the outer wing is in the pitch down state.[5]
Considering this point, bearing is mounted on the wrist joint so that the twist angle of the wing is formed.
In 2012, DGIST conducted research on flapping-wing model for aerial robot. Through this study, the articulated winging robot can obtain the ideal aerodynamic force when the length ratio between the inner wing and the outer wing is 1:2.[13] Therefore, the inner wing length was designed to be 30 cm and the outer wing length to 60 cm.

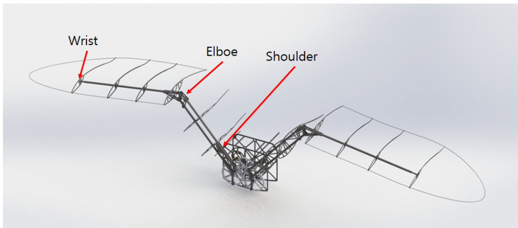

Figure 3: Wing mechanism

2.3 Kinematic analysis

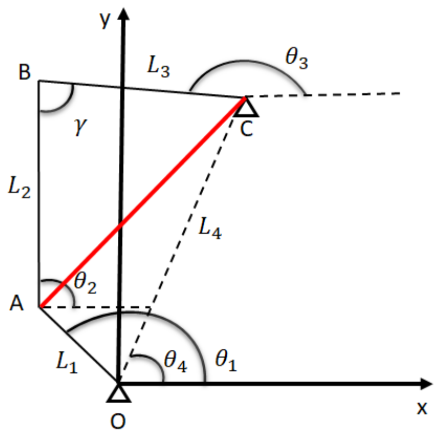

Figure 4: A schematic of the inner flapping wing mechanism

In this paper, the name of the articulated flapping robot designed and manufactured is USGull, and Figure 2 shows the wing mechanism of the flapping of the USGull. Fig. 2, the mechanism of the USGull is a four-bar link with a Crank-Rocker structure, named as follows. (L_1=Crank, L_2= Coupler, L_3= Rocker, L_4= Ground)
The derivation of transmission angle and the inner flapping angle is as follows.

$$\overline{AC} = \sqrt{L_1^2 + L_4^2 - 2L_1L_4cos(\theta_1 - \theta_4)} \quad (1)$$

$$\gamma = cos^{-1}\left(\frac{L_2^2 + L_3^2 - \overline{AC}^2}{2L_2L_3}\right) \quad (2)$$

$$\theta_3 = 2tan^{-1}\left(\frac{L_1sin(\theta_1 - \theta_4) - L_2sin(\gamma)}{L_1cos(\theta_1 - \theta_4) + L_3 - L_4 - L_2cos(\gamma)}\right) \quad (3)$$

γ is the transmission angle and should be within the range of 45°-135° because the four-bar link design needs satisfy the design conditions[14]. The larger the flapping angle and the span, the greater the thrust becomes.[15] In this paper, the span length is 1.8m, Θ_3 is the Inner flapping angle, the design condition of this paper is set to $L_1 = 29mm$, $L_2 = 65.2mm$, $L_3 = 63mm$, $L_4 = 86.9mm$. θ_4 = 67° which is the input value.

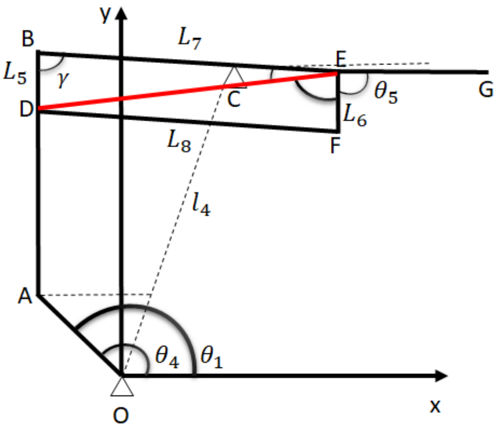

Figure 5: A schematic of mechanism in kinematics

For the outer wing mechanism (as shown in Fig. 5), to achieve the good performance, the quadrilateral mechanism (BDFE) should be a parallelogram. Thus, the folding angle of the inner and outer wing is writhen as eq.7

$$\overline{DE} = \sqrt{L_7^2 + L_5^2 - 2L_5L_7cos(\gamma)} \quad (4)$$

$$\angle BED = cos^{-1}\left(\frac{\overline{DE}^2 + L_7^2 - L_5^2}{2\overline{DE}L_7}\right) \quad (5)$$

$$\angle FED = cos^{-1}\left(\frac{\overline{DE}^2 + L_8^2 - L_6^2}{2\overline{DE}L_7}\right) \quad (6)$$

$$\angle Folding = \angle BED + \angle FED + \theta_5 \quad (7)$$

$\overline{DE}$ is a function of γ by Eq.(4) and γ is a function of $\overline{AC}$ by Eq.(2) and $\overline{AC}$ is a function of the input value by Eq.(1). In this paper, we set $L_5 = 25.5mm$, $L_6 = 25.5mm$, $L_7 = 249mm$, $L_8 = 249mm$ and θ_5 = 71°.

2.4 Simulation analysis

This paper verified the results by comparing the results of MATLAB with those of ADAMS in terms of transmission angle, inner flapping angle, folding angle. Input (Θ_1) is excited, and the result is shown in Figure 6-9.

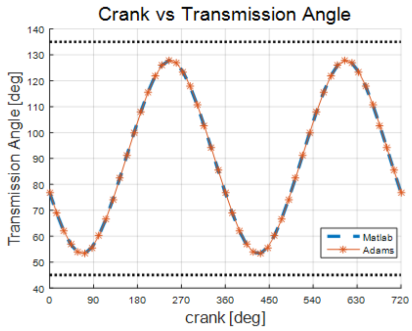

Figure 6: Crank vs Transmission algle

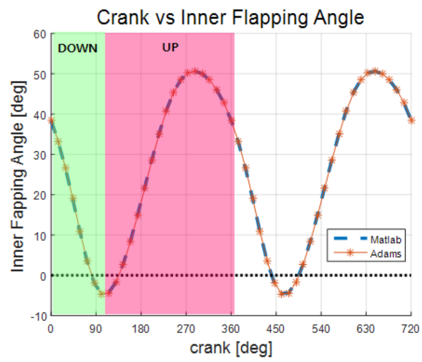

Figure 7: Crank vs Inner flapping angle

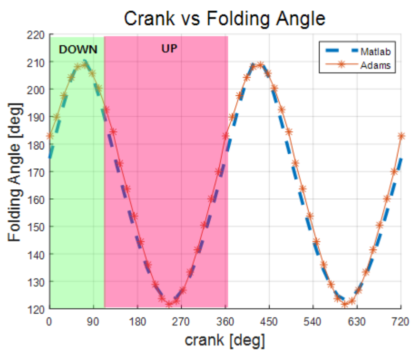

Figure 8: Crank vs Folding angle

2.5 USGull Prototype

In order to meet weight and durability, the frame was made with carbon plate, and EPP material was used as the skin. Figure 10 and Table 3 show the prototype and detailed specifications of the USGull respectively.

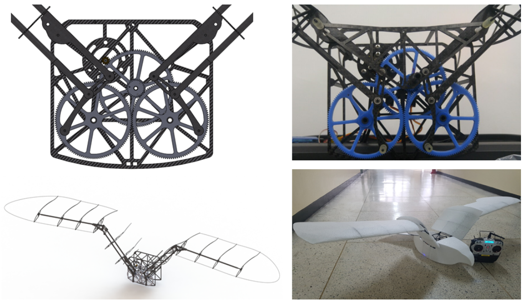

Figure 9: USGull prototype

Weght	460g	**Mean chord**	0.25m
Span	1.8m	**Aspect ratio**	6.8
Length	0.9m	**Skin**	EPP
Gear ratio	1:44	**Flapping Frequency**	2-3Hz

Table 3: USGull specification

3 Analysis with motion capture camera

As shown in Fig.10, the experimental environment of the motion capture camera was constructed and the kinematic design parameters were verified through this experiment.

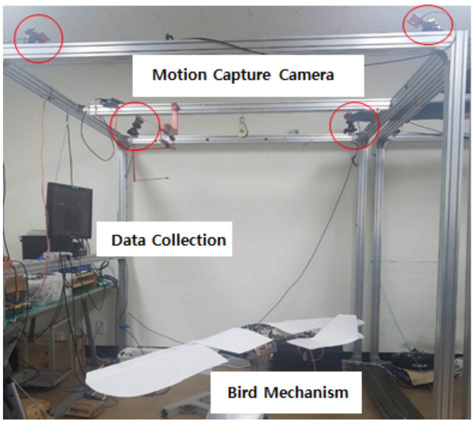

Figure 10: Experiment Environment

Fig.11-12 show the results of the analysis using the motion capture camera. It can be confirmed that the design parameters are designed so as to be equal to each other when compared with the kinematic equations and the ADAMS simulation obtained in Fig.7-8.

4 Thrust test with Load Balance

Thrust is an important factor when an aircraft takes off. This is true of birds flying. The research was conducted on the

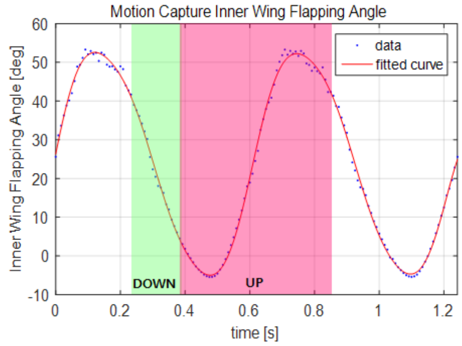

Figure 11: Motion Capture Inner Wing Flapping Angle

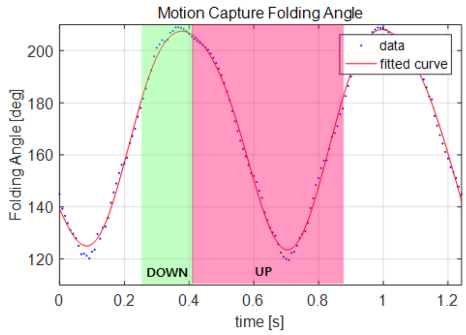

Figure 12: Motion Capture Folding Angle

optimal wing shape that can achieve maximum efficiency by utilizing UVLM simulation.[16] The conclusion of the study was that thrust was higher in the sweptback wing than in the straight wing.

In this paper, the thrust due to the wing movement, rather than the wind tunnel test environment, was carried out according to the wing area and wing shape. For the experiment, a one-axis load cell was used and the value of the change in thrust according to the angle was measured. The experimental environment is shown in Fig.13.

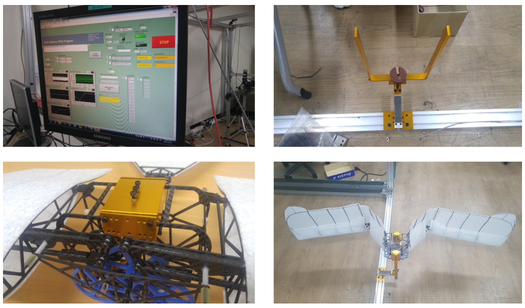

Figure 13: Experiment enviroment

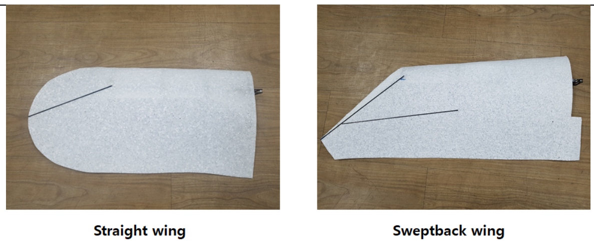

Figure 14: Wing shape

4.1 *Sweptback wing vs rectangular wing*

As shown in Fig.14, the comparison was made between straight and sweptback wings when the areas were the same (0.1352m^2).

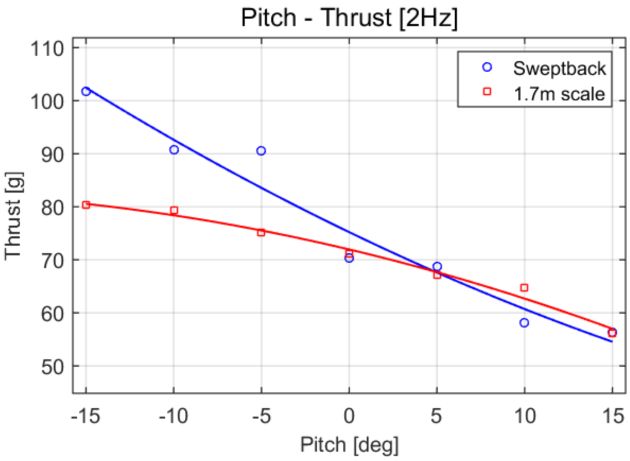

Figure 15: Thrust result of different wing shape

Fig.15 shows the results of the thrust test. Overall, the thrust shows a maximum at -15°. This is because the thrust due to the wing is higher than the center of gravity. Also, it was confirmed that when the pitch angle is negative with respect to the pitch angle of 0°, the thrust of the sweptback wing is increased by about 20% than the rectangular wing.

4.2 *Comparison of rectangular wings with different wing areas*

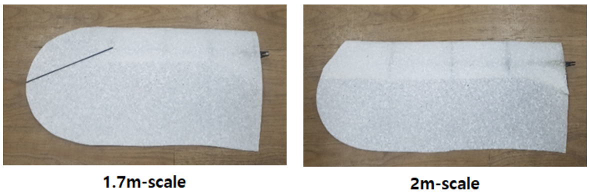

Figure 16: Same shape with defferent area

Fig.16 shows a straight wedge with the different area. The area of 1.7m-scale is 0.1352m^2, and the area of 2m-scale is 0.1716m^2. The span length is 2m-scale longer than 1.7m-scale and about 15cm longer.

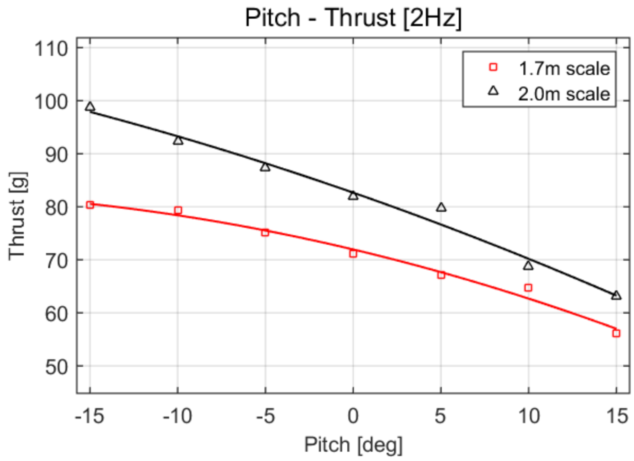

Figure 17: Thrust result of different wing area

Fig.17 shows the results of the thrust test. As shown in the graph of Fig.15, the maximum thrust is found at -15°. Also, the larger the area, the greater the overall thrust. However, as the wing area increases, the load on the elbow joint increases and the flapping mechanism becomes unstable. Therefore, it is necessary to adopt a double elbow joint to make a structural complement.

5 Preliminary Flight Test Results

Figure 18: Flight Test

We conducted a preliminary flight test and performed a performance test on the USGull with 1.7-scale. It is believed that maneuverability and stability are secured. However, due to the periodical wing movement, there was a structural problem of the elbow joint and the flight performance was not as good as desired.

6 Conclusions and Future work

In this paper, an articulated ornithopter was designed and fabricated through kinematic modification and verification.

kinematic parameter design verification was performed using a motion capture camera. Also, the thrust test was performed according to the wing shape and area, and the results were compared and analyzed. Finally, the stability and maneuverability of the ornithopter were analyzed through the flight test, but due to the structural problems on the elbow joint, the continuous flapping movement was not performed.
After the elbow joint is structurally reinforced, the flight test will be conducted and the system identification will be carried out on the articulated ornithopter using the flight data.

ACKNOWLEDGEMENTS

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