Research Paper
International Journal of Aerospace System Engineering
Vol.3, No.2, pp.26-30 (2016)

ISSN 2383-4986
http://dx.doi.org/10.20910/IJASE.2016.3.2.26

The Effect of Folding Wing on Aerodynamics and Power Consumption of a Flapping Wing

Seunghee Lee[1], Cheolheui Han[2†]
[1]*Graduate School of Mechanical Engineering, Hanyang University, KOREA*
[2]*Department of Aeronautical and Mechanical Design, Korea National University of Transportation KOREA*
[†]*E-mail:chhan@ut.ac.kr*

Abstract

Experimental study on the unsteady aerodynamics analysis and power consumption of a folding wing is accomplished using a wind tunnel testing. A folding wing model is fabricated and actuated using servo motors. The flapping wing consists of an inboard main wing and an outboard folding wing. The aerodynamic forces and consumed powers of the flapping wing are measured by changing the flapping and folding wings inside a low-speed wind tunnel. In order to calculate the aerodynamic forces, the measured forces are modified using static test data. It was found that the effect of the folding wing on the flapping wing's total lift is small but the effect of the folding wing on the total thrust is larger than the main wing. The folding motion requires the extra use of the servo motor. Thus, the amount of the energy consumption increases when both the wings are actuated together. As the flight speed increases, the power consumption of the folding wing decreases which results in energy saving.

Key Words : Wind Tunnel Testing, Aerodynamic Forces, Flight Performances, Folding Wing

1. Introduction

Along with the recent progress in smart materials and actuators, micro air vehicles or aerial robots that mimics the animal flights in nature have been developed or under construction. Historically, the study on the flight was initiated with avian wings. Recently, the study on the biological flight in nature has been more focused on the elucidation of the insect flight because insects can hover, climb, and descend easily with amazing stability. Many of the questions on the dynamic flight stability and flight control mechanisms of insects have been cleared.

Compared to the small-sized insects, birds flap their relatively large wings with low frequency [1]. Due to the large size and heavy mass compared to the insect, the birds' agility cannot be obtained while the insect can have[1-3]. However, birds in nature can flap their primary wings while simultaneously folding their secondary wings. The wing folding is the interesting feature of the bird flight which is not shown in the insect flight. The use of wing folding can be used with diverse purposes.

Recently, a bird-mimicking flight model, SmartBird, was developed by German company, festo[4]. SmartBird can start, fly, and land autonomously. It weighs only 450g with a wing span of 1.96m. It can actively twist its wings at specific angles, while beating its main wing up and down, by using an actively articulated torsion drive. The wing folding is passively accomplished by using a constraint in the folding joints.

Among the study on the bird flight, the effect of the folding wing on the aerodynamics and power consumption has not been published much in the

---

Received: Nov 28, 2016 Revised: Dec 21, 2016 Accepted: Dec 21, 2016
† Corresponding Author
Tel: +82-43-841-5379, E-mail: chhan@ut.ac.kr

literatures[5,6]. Thus, the aim of the present paper is to investigate the effect of the wing folding on the aerodynamics and power consumption of the flapping flight. The active actuation mechanism of the bird's folding is devised and the aerodynamics and power consumptions of the folding wings are measured using a wind tunnel test.

2. Experiments

2.1. Mechanism of Folding Wings

The kinematical actuation of folding wings requires many degrees of freedom. However, the increase in the number of the motors will complicate the system configurations. The motor should sustain the weight of the wing and be able to move the main and outer folding wings. The important aspect in the design of folding wing actuation mechanism is that the inertia of the main wing should be minimized. The idea of overcome this constraint is the use of a tendon for actuating the outer wings, through which the use of extra motor required for actuating the outer wing can be avoided. As shown in Fig. 1, the actuator system is designed to have 3-DOFs and each motors are assembled together. The tendon in a tube could move the outer wing with the precision required for the test. The volume of the device was very large and could not fit inside the body, thus, another mechanism is devised by using two motors as shown in Fig. 2. The motor 2 used for the wing folding is aligned with the motor 1 and the frame for the main wing is attached to the motor2. A pulley system is attached to the end of the main wing frame. The outer wing is connected to the pulley and the rotation of the pulley makes the outer wing folded. The frame of the main wing has a C-shape aluminum plate with the section area of 24 (mm) × 9 (mm) and 2 mm thickness.

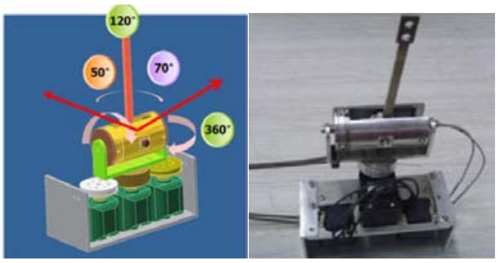
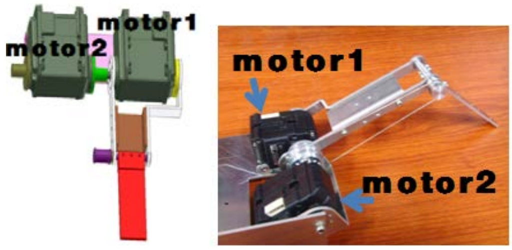


Fig. 1 Actuation mechanism of wing folding

2.2. Wind Tunnel Testing

A wind tunnel test model is fabricated by mimicking the shape of seagull wings. The test model wing consists of two parts(main and folding wings). The maximum length of the model wing is 580mm. The flapping angle of the main wing and the folding angle of the folding wing are 60 and 70 degrees, respectively. The wingtip displacement is 89 mm and the flapping frequency of the wing is 3.5Hz. Both wings can be controlled separately. USB2-485 was used as a communication interface board (11,000 bps) in order to control the wing motions with given inputs from the PC. Labview^{TM} software was utilized for the control inputs. The test model is composed of mechanical devices, a model positioning system, and a force/torque sensor. MINI40(force/torque sensor) was used for the measurement of the aerodynamic forces and moments. The output signal is transferred to a transducer converter and NI PCI-6229 DAQ board.

Figure 4 shows the data processing procedures used in this study. Fig. 4(a) shows the raw data obtained



(a) actuation model

(b) W/T test model

Fig. 2 Actuation mechanism designed for wing folding and W/T test model

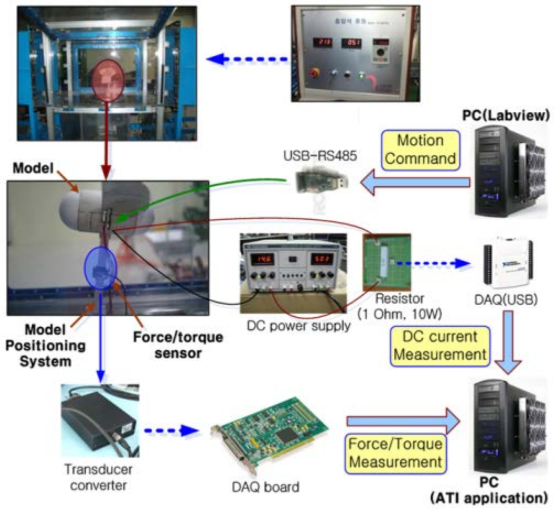
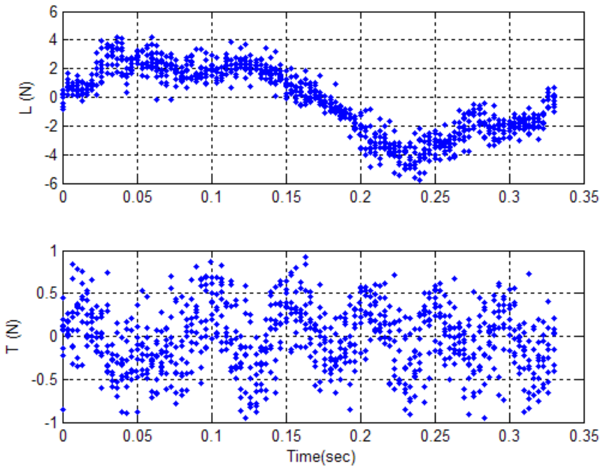
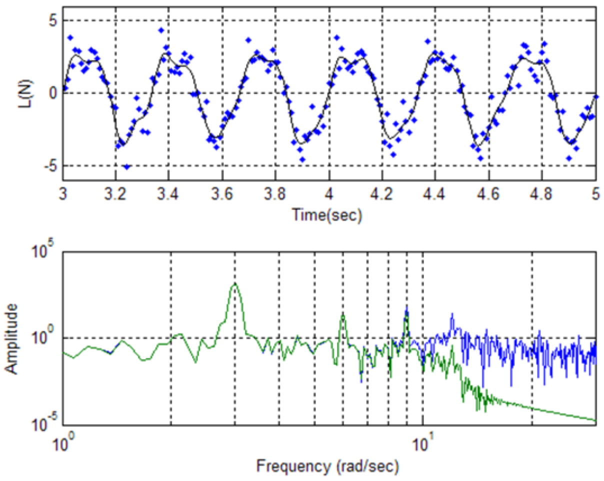


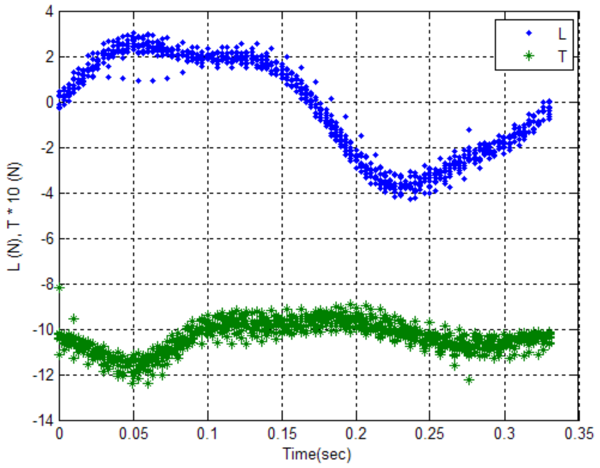
Fig. 3 Data acquisition system



(a) raw data from F/T sensor



(b) Frequency analysis and low pass filtering



(c) Data obtained from filtering

Fig. 4 Data processing using low pass filtering

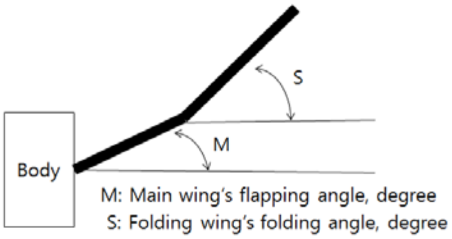


Fig. 5 Nomenclature of the flapping and folding angles

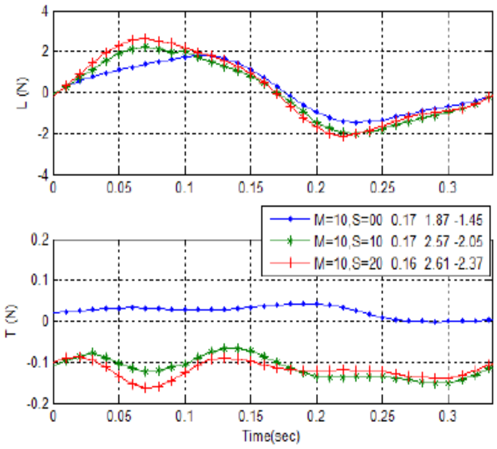
from the F/T senor. The raw data are filtered through low pass filtering. The high vibration of the system caused by the flapping motion produces the fluctuated data as shown in Fig.4(a). The aerodynamic forces generated by the low frequency flapping motions are assumed to make little contribution to the high harmonics. A low pass filter with a cutoff frequency three times larger than the flapping frequency was used to filter the measured raw data (See Fig. 4(b)). Fig. 4(c) shows the filtered data as a function of time. The mean value of the data at a given time was assigned as the final data at that time.

Figure 5 shows the definition of flapping and folding angles. The wing model is separated as the two wings: main wing and sub wing. The flapping angle defines the angle between the inboard wing (main wing) and horizontal plane. The folding angle defines the angle between the outboard wing (folding wing) and the horizontal plane. When the main wing's flapping angle is 10 deg. and the sub wing's folding angle is 5 deg., the wingtip becomes the angle of 15 deg. from the horizontal plane.

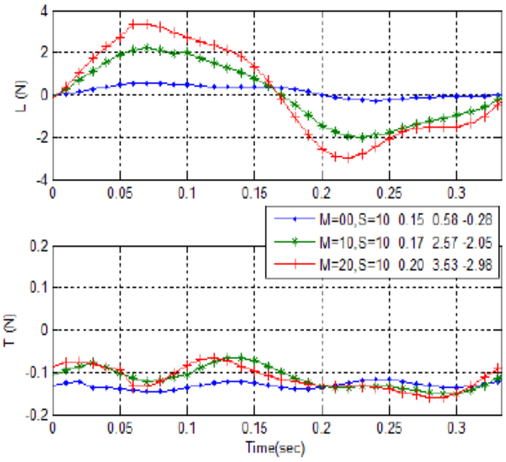
3. Results and Discussion

Figure 6 shows the time variation of lift and thrust due to the flapping and folding motions of the wing. Fig. 6(a) shows the lift and thrust time histories when the flapping angle of the main wing is set to 10 deg. and the folding angles of the folding wing are changed from 0 deg. to 20 deg. Fig. 6(b) shows the lift and thrust time histories when the angle of the folding wing is fixed to 10 deg. and the flapping angles of the main wing are changed from 0 deg. to 20 deg., respectively. The wing model is placed in parallel to the uniform stream. Thus, the angle of attack to the body is 0 deg. The period of the wing motions is set to 0.35 sec. The negative value in the thrust means the positive thrust. During the half period, the wings perform downstroke motions. After the given half period passed, they undergo upstroke motions. As shown in the figure, the downstroke motion increase the angle of attack to both wings and generates the lift. When the wings undergo the upstroke, the negative lift also starts to be generated due to the negative angle of attack. When the flapping angle of the main wing is 20 degrees and the folding angle of the folding wing is 10 degrees, the generated lift has the largest value. As shown in the figures, in the aspect of the lift generation, the flapping angle of the main wing has larger effect than the folding angle of the folding wing. The effect of the folding angle on the lift is shown to be very small.

As shown in the Fig. 6(a), the folding wing has a significant to the generation of the thrust. Compared to the case of zero folding angle, the 10 and 20 degree folding angles produced positive thrusts. When the folding angle is fixed and the flapping angle is changed (Fig. 6(b)), the change of the thrust due to the flapping angle is not significant. Thus, it can be said that the folding angle plays more significant role in increasing the thrust.



(a) M=10 deg.(Blue: S=0.0, Green: S=10, Red: S=20)



(b) S=10 deg.(Blue: M=0.0, Green: M=10, Red: M=20)

Fig. 6 Change of the lift as a function of time

Figure 7 shows the power consumption of the folding wing (the flapping angle of the main wing is fixed to 0 deg.) as a function of flapping frequency. As shown in Fig. 7, the power consumption is increased as a nonlinear function of the flapping frequency. The higher folding angle makes the wing consume more energy. When the folding angle is set to 20 degrees, the required power for the flight is decreased with the flight speed stepping up. However, when the folding angle is set to 10 degrees, it is not clear if the flight speed has an effect of decreasing the power consumption. More detailed study on the phenomena should be accomplished.

Figure 8 shows the power consumption while performing the wing motions. The angle of angle of the body is set to 10 degrees. As shown in the figure, the consumed power of the test model decreases

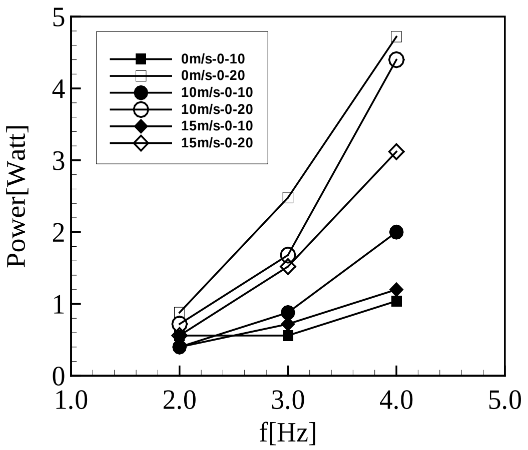


Fig. 7 Consumed power as a function of flapping frequency

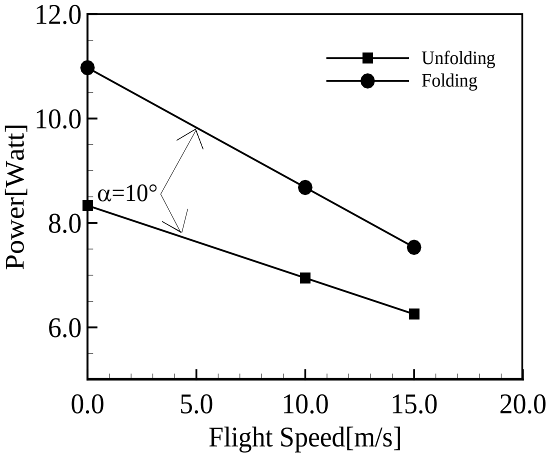


Fig. 8 Comparison of consumed power between folding and unfolding wings

linearly as the flight speed increases. The folding motion requires more power, but as the flight speed increases the difference in the consumed powers between the folding and flapping wing is reduced.

4. Conclusions

In this paper, we fabricated the wind test model by mimicking the seagull wing shapes. The actuation of the folding wing is accomplished using servo motors. The configuration of the servo motors is designed so that the numbers of the motors are minimized.

The effect of the folding wing on the lift generation is not so significant, but the effect of that wing on the thrust generation is large compared to the main wing. The folding motion requires the extra use of the servo motor. Thus, the amount of the power consumption increases when both wings are actuated together. However, as the flight speed increase, the power consumption of the folding wing decreases which results in energy saving.

References

[1] A. Azuma, *The Biokinetics of Flying and Swimming*, AIAA Education Series, 2nd Ed., AIAA Inc., Reston, Virginia, 2006.

[2] K. V. Rozhdestvensky, V. A. Ryzhov, "Aerohydrodynamics of flapping-wing propulsors," *Progress in Aerospace Sciences*, Vol. 39, pp. 585-633, 2003.

[3] S. Ho, H. Nassef, N. Pornsinsirirak, Y. C. Tai, C. M. Ho, "Unsteady Aerodynamics and Flow Control for Flapping Wing Flyers," *Progress in Aerospace Sciences*, Vol. 39, pp. 635-681, 2003.

[4] https://en.wikipedia.org/wiki/SmartBird

[5] T. J. Muller(ed). *Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications*, Progress in Astronautics and Aeronautics, AIAA Inc. Reston, Virginia, 2001.

[6] C.J., Pennycuick, *Modelling the Flying Bird*, Academic Press, 1st Edition, 2008.