3EB12.P

TRANSDUCERS & EUROSENSORS '07
The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, June 10-14, 2007

# SMART FLAPPING WINGS WITH A PVDF SENSOR TO MODIFY AERODYNAMIC PERFORMANCE OF A MICRO UAV

**Lung-Jieh Yang[1], Cheng-Kuei Hsu[1], Chao-Kang Feng[2], H.-M. Shih[1], G.-H. Feng[1] and M.-W. Gao[1]**
[1] Department of Mechanical & Electromechanical Engineering, Tamkang University, Tamsui, Taiwan R.O.C.
(Tel : +886-932-159193; E-mail: Ljyang@mail.tku.edu.tw)
[2] Department of Aerospace Engineering, Tamkang University, Tamsui, Taiwan R.O.C.

***Abstract:*** This paper describes a new configuration of flapping wings to study the aerodynamic behavior of a micro UAV (unmanned aerial vehicle.) The flapping wings are composed of a pure parylene right wing and a PVDF-parylene composite left wing on purpose. The PVDF (polyvinylidene fluoride) sensor could only export the lift signals from the left wing. In comparison to the total lift signal picked by the load cell from the wind-tunnel facility, we can figure out and separate the lift contributions donated by left wing and right wing, respectively. Therefore, we found a new design methodology to adjust the aerodynamic performance of micro UAVs by changing the phase lag between the two flapping wings through fine tuning the mechanism linkages.

**Keywords:** *Micro UAV, polyvinylidene fluoride, flapping wing.*

## 1. INTRODUCTION

How to predict lift force of a flying is a very critical issue in the design of a micro UAV. Actually, measuring the instantaneous aerodynamic force on a flapping model or live insect remains a great challenge in experimental aerodynamics. The early surveys of measuring averaged force focus on using delicate balances [1-2]. Other prior researches used piezoelectric probes [3], strain gauges [4] and the laser interferometers [5]. By the size constraint of measuring tools, people assume all the wings behave identically and have the equal force contribution to the flying body. Therefore, more efforts and cost should be paid on fabricating the very dedicate and identical wing structures in the conventional development of micro UAVs.

The on-site lift information acquired from a PVDF sensing skin was done by the authors of this work [6]. In ref. [6], we employ four-linkage concept to design a transmission mechanism shown in Fig. 1. Although the two wings have the same flapping angle of 39~61 degrees, there exists unavoidably a mechanical phase lag of 2.5~13 degrees between them due to the gear-transmission's essence of mechanical design (see the simulated data in Fig. 2.) We would describe the mechanism design of the transmission system more clearly as below.

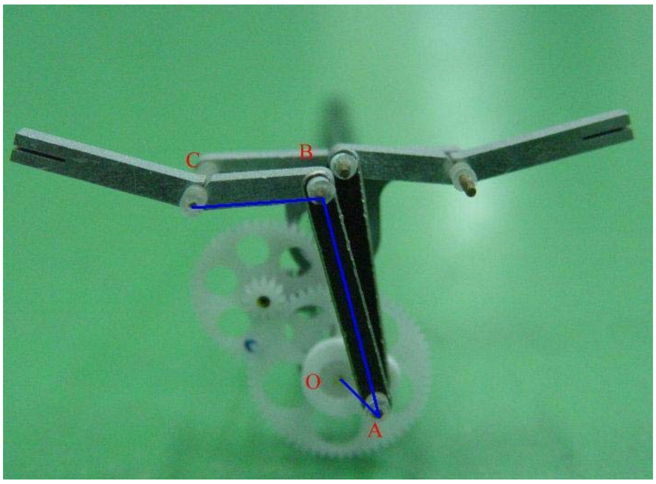



*Fig. 1 The fabricated transmission mechanism.*

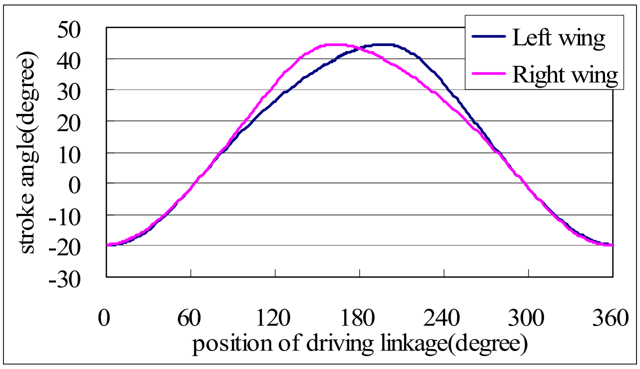



*Fig. 2 Stroke angles of two flapping wings vs. one period of time.*

## 2. TRANSMISSION SYSTEM DESIGN

The transmission system of Fig. 1 for the micro

TRANSDUCERS & EUROSENSORS '07
The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, June 10-14, 2007

UAV is composed of a gear-reduction set and a four-bar linkage. We use a 7mm-diameter DIDEL electric motor to drive this transmission system. The gear set with a gear ratio of 26.6 adopted herein provides sufficient torque for driving the flapping wings. The whole gear set and the motor are arranged on an aluminum base. OA is the driving linkage and the following linkage BC is connected to the wing structure. The driving linkage can rotate a revolution completely and the following linkage undergoes a rocking motion. We can easily get different stroke angles and flapping symmetry (the lag phenomenon between the two wings in the flapping motion) by adjusting the dimensions of linkages OA, AB and BC. The selected lengths for each linkages are OA=4 mm, AB=21.5 mm. With variable lengths of linkage BC from 8 mm to 12 mm, there are correspondingly large changes of stroke angles and phase angle lags (max) in flapping movement, as seen in table 1.

*Table1 1 Designs of the transmission system*

| BC(mm) | stroke angle | lag(max) |
|---|---|---|
| 8 | 60.5 | 13.3 |
| 9 | 53.0 | 9.4 |
| 10 | 47.2 | 6.4 |
| 11 | 42.7 | 4.1 |
| 12 | 39.0 | 2.5 |

## 3. MEMS WING FABRICATION

We use MEMS technology for the wing fabrication to ensure the accurate size control of the flapping wings. The material of airframes is titanium alloy (the mechanical properties of titanium grade 4: density = 4.54 g/cm$^3$; Young's modulus = 104 GPa; tensile strength = 552 MPa). Wet etching technique is accessed to tailor the airframe structures from a titanium alloy plate with no apparent residual stress, and parylene coating technique is applied to laying the wing skin attached on the titanium frame, respectively.

The fabrication process of titanium-alloy MEMS wings with 25μm-thick PVDF film is shown in Fig. 3 and described as below.

- Step (a): A titanium-alloy substrate is cleaned with acetone, isopropyl alcohol (IPA) and de-ionized (DI) water sequentially.
- Step (b): Both sides of the titanium-alloy substrate are spin-coated with photoresist (PR) AZ4620. Exactly control the rotation speed to get 10μm thick PR.
- Step (c): The upside PR is patterned as an etching mask for the titanium-alloy frame.
- Step (d): The titanium alloy substrate is etched by hydrofluoric (HF) acid for 50 minutes. The geometry of wing frames then appears.
- Step (e): Strip PR from both side of titanium-alloy surface by acetone and clean all parts again.
- Step (f): The first parylene film of 11.5μm thick as insulated layer is deposited on titanium alloy by the parylene coater (SCS PDS-2010). For this step, 15g of parylene dimmer is used.
- Step (g): A piezoelectric foil of PVDF is pasted on the frames.
- Step (h): Coat the PVDF film and the wing-frame with the second parylene layer.

The PVDF-parylene composite flapping wings after processing is shown in Fig. 4(a). Fig. 4(b) shows the flapping model installed on a load cell in a wind tunnel.

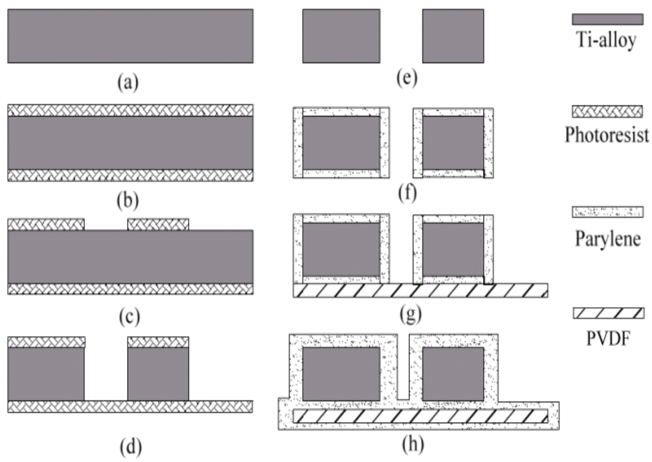



*Fig. 3 Process flow of a PVDF-parylene wing.*

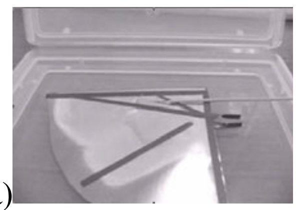
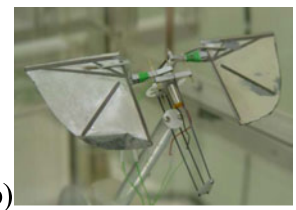
(a)  (b) 

*Fig. 4 Micro UAV model: (a) The completed PVDF-parylene flapping wing. (b) Setup for testing the flapping wings with PVDF sensing skin in the wind-tunnel.*



1-4244-0842-3/07/$20.00©2007 IEEE

## 4. EXPERIMENTAL SETUP

The aerodynamic testing of the micro UAV in this work was conducted in a small wind-tunnel. The dimension of the test section is 30×30×100 $cm^3$ and the inlet contraction ratio is 6.25:1. The load cell (Bertec, OH, USA) with specifications of 200g and 100g are responsible for the force measurement of lift and drag, respectively. And it has the maximum error 0.2% of the full-scale signal due to the linearity or hysteresis. In the wind tunnel testing, the micro UAV is placed on the load-cell directly to acquire the data of aerodynamic forces, and the PVDF signal is also exported in an on-site way simultaneously. We apply a fixed voltage of 4 volts for driving the flapping wing. The angle of attack is fixed as 45 degrees in the wind-tunnel tests herein. Fig. 5 shows the experimental setup.

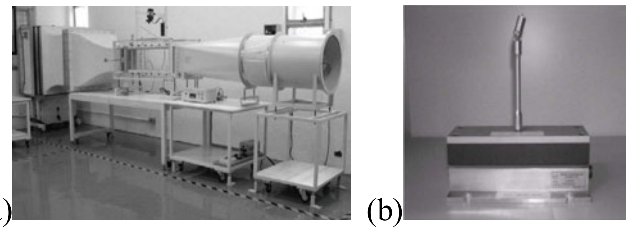
(a)  (b)

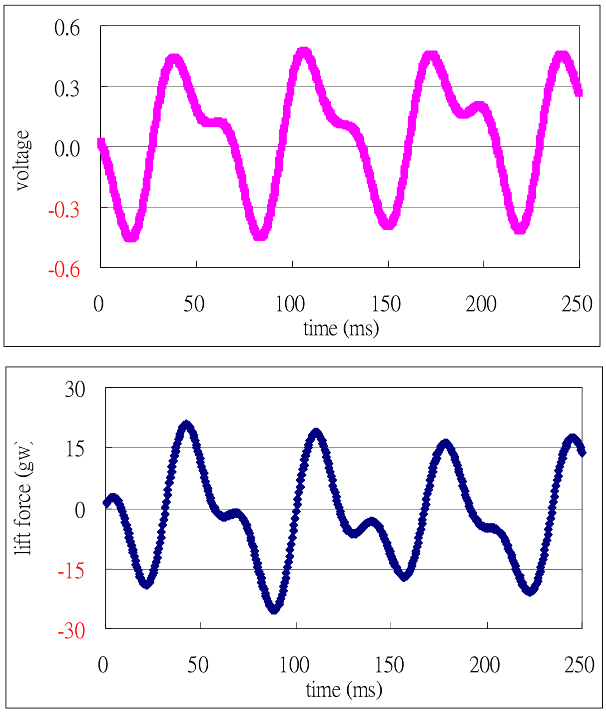
*Fig. 5 The wind-tunnel test system: (a) Low speed wind-tunnel; (b) Load cell (Bertec Corp.)*

## 5. RESULT AND DISSCUSTION

The aerodynamic signals are picked up successfully by PVDF and load cell simultaneously. While the linkage BC is 11mm, the collected lift data are shown in Fig. 6. From the first glance, a phase delay between the PVDF signal (Fig. 6(a)) and load cell signal (Fig. 6(b)) can be observed. The real situation is that we only assign the left wing composed of a PVDF sensing skin and the right wing is pure parylene. The signal from the PVDF film denotes the lift information of the left wing, not including the right wing. Meanwhile, the signal from the load cell concludes the global forcing effect from both two wings. With variable lengths of linkage BC, the phase lag of the two wings resulted in the curve of PVDF is ahead or behind the load cell.

By superimposing a similar curve of Fig. 6(a) with a proper phase lag (11 degree) into Fig. 6(a) itself, we can get the "pseudo" result in Fig. 7 which matched with Fig. 6(b) very well in a qualitatively way. How to know the proper phase lag for superimposition? In fact, we accurately superimpose by mathematical method, from 0 to 27 degrees, and use the standard deviation to define the similarity between the pseudo PVDF and load cell curve. We find the phase lag of 11 degree is the most fitting case, as shown in Fig. 8.

What's revelation from the new configuration of the flapping wings? Because the phase lag of the gear-transmission system is inevitable in the mechanical design, we turn to make the most of this characteristic to enhance the lift behavior of micro UAVs. For example, we can make the lift curve smoother to sustain a better attitude of the UAV during the flapping cruise. After figuring out the relationship between the phase lags from gear-transmission and lift response in Fig. 9, we'd like to adjust the aerodynamic performance of micro UAVs reliably by changing the phase lag between the two flapping wings through fine tuning the mechanism linkages of the gear-transmission system.



(a) (b)

*Fig. 6 Lift signals of the MAV from (a) PVDF film and (b) load cell.*

TRANSDUCERS & EUROSENSORS '07
The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, June 10-14, 2007

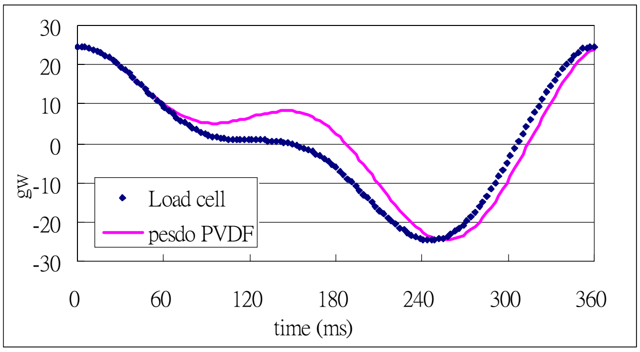



*Fig. 7 The "pseudo" signal comes from superimposing a similar curve of Fig. 5(a) with a proper phase lag (11 degree) into Fig. 5(a) itself.*

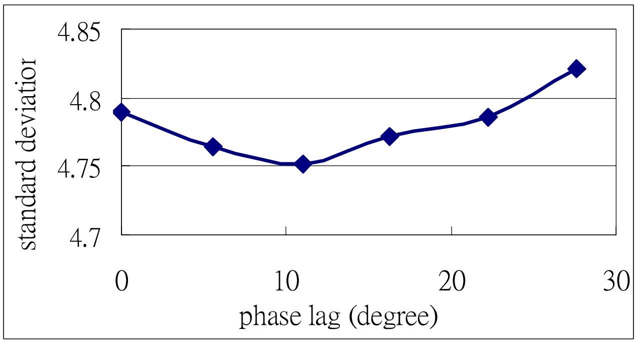



*Fig. 8 By using the standard deviation to judge the similarity.*

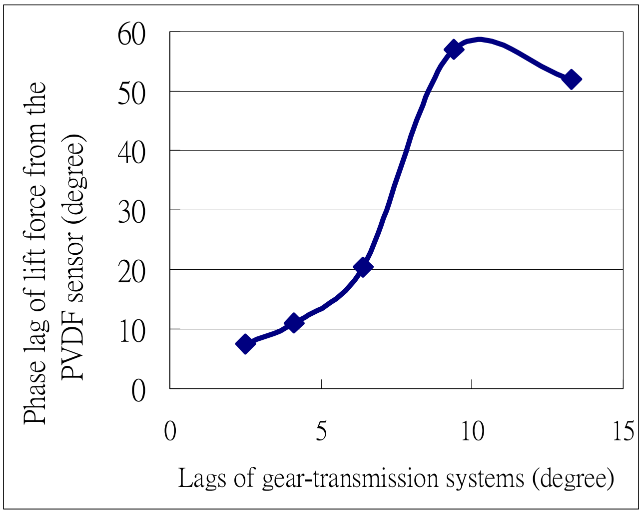



*Fig. 9 Deduced phase lag of lift force from the PVDF sensor vs. different lags of gear-transmission systems.*

## 6. CONCLUSION

This study constructs a smart wing with PVDF-parylene composite wing by MEMS fabricating process and a four-bar linkage transmission system with variable phase lags of the flapping wings. The signals from the PVDF film and the load cell are acquired simultaneously and the curves are quite similar. The collected data has a phase lag between the PVDF and load cell curve due to the design of asymmetric flapping movement. By a superimposing method, the "pseudo" PVDF curve has higher similarity to the lift signals. The smart PVDF-parylene composite wing and the superimposing method can help us to design a micro UAV with ideal aerodynamic characteristic by changing the phase lag between the two flapping wings through fine tuning the mechanism linkages.

## ACKNOWLEDGEMENT

The authors thank the financial and travel support from National Science Council of Taiwan ROC with the project number of NSC-95-2221-E-032-036, 037.

## REFERENCES

[1] F.S.J. Hollick, "The flight of the dipterous fly Muscina stabulans Fallen," *Phil. Trans.*, B 230, 357-90, 1940.

[2] M. Jensen, "Biology and physics of locust flight. III. The aerodynamics of locust flight," *Philosophical Transactions of the Royal Society of London*, Series B, Biological Sciences, 239(667), pp. 511-552, 1956.

[3] M. Cloupeau, "Direct measurements of instantaneous lift in desert locust: comparison with Jensen's experiments on detached wings," *J. Exp. Biol.*, 80, pp. 1-15, 1979.

[4] S. Ho, H. Nassef, T. N. Pornsinsirirak, Y. C. Tai, "Unsteady aerodynamics and flow control for flapping wing flyers," *Progress in Aerospace Science*, 39, 635-681, 2003.

[5] M. H. Dickinson, K. Götz, "The wake dynamics and flight forces of the fruit fly Drosophila melanogaster," *J. Exp. Biol.*, 199(99), pp. 2085-2104, 1996.

[6] C.-K. Hsu, J.-Y. Ho, G.-H. Feng, H.-M. Shih and L.-J. Yang, "A flapping MAV with PVDF-parylene composite skin," Proc. of APCOT-2006 (SASN-A0019), Singapore, Jun. 25-28, 2006, p. 253.



1-4244-0842-3/07/$20.00©2007 IEEE