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The Micro Aerial Vehicle (MAV) with Flapping Wings

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Abstract— **The research of micro aerial vehicles (MAVs) is a new field of low-Reynolds-number flow, which attracts much attention in the advanced aeronautical area. The flapping wing, proved by many natural flyers, is the most appropriate way of flying objects which sizes are less than 6 inches. However, there is still plenty of room for studying on the unsteady aerodynamic characteristics of flapping wings. The flapping wing, which is light weighted and high strengthened, is originally composed of the titanium-alloy frame and the parylene skin. Such an integration of fabrication needs the help of MEMS processing. Additionally, the flapping test after the wing fabrication and the corresponding signal analysis from the smart wing skin will conclude this project and set the bases for the wind-tunnel verification/correction in the very near future.**

I. INTRODUCTION

This research attempts to fabricate a MAV by using the mature micro electro mechanical system (MEMS) manufacturing technology. The MAV definition made by Defense Advanced Research Projects Agency (DARPA) includes size-limitation and performance of air vehicle [1]. The size constraint on vehicle is total wingspan less than 15 cm in dimension, highest velocity is about 48km/hr, endurance is about 10km, flying time is about 20-120 minutes. According to flying motion, MAV can be classified: fixed-wing, propeller wing and flapping wing. Up to the present, still many national military and academic departments had invested a lot of resource in developing MAV. Among all flying modes, the flapping wing is most suitable for MAV. Although these previous works of MAV got successes for flying by wireless real-time control, the unsteady aerodynamic characteristics of the flapping MAVs are still unclear and mysterious. Although, it still has a lot of pending problems about its unsteady aerodynamic characteristics.

Flapping is restricted too limited operations such as taking off, landing, or stabilization. When soaring, the wings are used as fixed-wing airfoils. For the smaller size of flyers, the less of such mechanism is employed. Small birds and insects, such as hummingbirds, bee, or flies, nature indicates that flyers of small sizes use the flapping wing mechanism to generate loft to overcome their own weight. Thus flapping is by far the most advantageous mechanism for flyer at these sizes when compared to mechanisms employing for fixed or rotating wings.

Total weight, including an airframe, flapping wings, an actuator, a controller and a power system, of the most light aerial vehicle of nowadays produced by using MEMS based technology by Caltech micromachining lab is 11.69 grams[2-3]. They used titanium alloy as a frame of the flapping wing and took a polymer material, parylene, as a covering skin of the airfoil. This integrated structure can bear a high frequency, more than 30 Hz, vibration and its weight is only 0.3 grams. Weight of the actuator and power system is about 5 grams. The MAV made by Caltech micromachining lab can be remote controlled manually and the flying endurance is more than 6 minutes.

Stanford Research Institute (SRI) used piezoelectric polymer material, so called artificial muscle, which its strain can attain to 100 % to drive the flapping wing [4]. They transformed an electric current into a continued expand and contract motion to drive the flapping wing and simulated a more complex flying mechanism.

Vanderbit University utilized a mature fabrication technology of a creeper driven by a piezoelectric material to simplify a mechanism of the flapping wing [5]. Sitti et al. mimicked a flight motion of a fly, Calliphora, to produce a micromechanical flying insect (MFI). They had a succession of investigations about aerodynamic of a multi-dimension flapping wing connecting with a special designed thorax structure. This transmission structure can drive a complex flapping motion to enhance a flapping frequency of MFI about 150 Hz. The transmission mechanism is driven by a piezoelectric material and its weight, airfoil span is 100 grams, 25 centimeter height [6].

Georgia Tech Research Institute (GTRI) took a motive force supplied by a reciprocating chemical muscle to drive a MAV which has two pairs of flapping wings where located on the two ends of the airframe. The weight of the MAV and the wing span are 50 grams and 15 centimeter [7].

Cambridge University research identified this flapping motion in insects can hover [8]. The flapping motion of the Mentor prototype is driven by "artificial muscles," which are actuators fabricated from electrostrictive polymer. The technology used is called "EPAM," for Electrostrictive Polymer Actuated Muscle, in which elastomeric actuators are contracted and relaxed by means of rapid jolts of high voltage up to 5000 volts. Most recently, brief successful tethered flights have been achieved.

There are many MAV programs that are being developed as mentioned before, but none of the programs have been able to achieve a long and sustainable flight. Therefore, in order to get more information in flapping situation, this work proposed the integration of PVDF piezoelectric foils to the parylene wings to pick up the in-situ lift force preliminarily. In order to obtain the realistic flapping situation of MAV

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during maneuver, we first implement a Caltech-like MAV as well as its several key components. First, we use MEMS-based technology to fabricate a titanium-alloy wing frame and a set of transmission mechanism and deposit parylene thin film on the frame as covering skin of the air-foil [8]. The transmission force taken to drive a transmitting mechanism made up of reduction gear sets with a DC motor powered by lithium batteries. The parylene can be used as an isolation layer to isolate the conduction between polyvinylidene-difluoride (PVDF, a polymer piezoelectric material) and Titanium. Our preliminary results will propose the novel approach, integration of parylene-PVDF as flapping-wing, on-site sensing element to monitor the lift force of MAV in wind-tunnel test system.

II. DESIGN CONCEPT

The weight of an air vehicle, including a flapping-wing flight vehicle, is a very critical parameter, however, a lift and thrust forces produced by a wing flapping are increased with a size of the airfoil. It is a key point to reduce the weight of a MAV as far as possible to design a flapping-wing flight vehicle. For this reason, adopt the titanium-alloy which is high strength-mass ratio to take for the air frame of flapping-wing. Meanwhile, look for the light weight and high power battery consequently. To fabricate accurate size for titanium-alloy with no residual stress is not easy by traditional machining technology. Just like forging, milling or punching are not suitable. Only a little stresses could cause a warping or any defects in the frame. Therefore, decide using the MEMS technology to help.

A. Design of airframe

The flight modes of birds could be classifies two types, one is gliding mode and the other is flapping mode. In order to imitate the gliding mode of birds flight, our design having a cambered rib to contribute the lift force without flapping at various wind speed. It is similar to the gliding mode of birds or fixed-wing vehicles. The primary purpose of flapping mode is to probe into the flapping frequency relates to the lift force at various wind speed. So to design the wings is a quite critical issue.

We use ripe MEMS technology to fabricate the wings, shown in Fig. 1, the material is titanium alloy (titanium grade 4, some mechanical properties are listed in TableI below). The two wings are jointed with a transmission system and both of them have span- and chord- length of 7 and 5.5 cm. The wing span is 90 degree in orientation to the wing chord. Among the two frames place a cambered rib which included angle is 45 degree to each side. In a way, it enhances the stiffness of globe wing. This design results forward thrust force with flapping-wing motion and sense the lift force on-site by integrated PVDF foil. Furthermore, the on-site measurement could be compared with a data of wind tunnel test.

B. Design of transmission

The MAV deceleration system composed of a reduction gears set to adjust torsion and rotational speed outputted by a DC motor, shown in Fig. 2. The gears set slow down the rotation speed of driving motor and raise higher torsion export to flapping-wing. This deceleration rate reaches 27.7. The gear set is arranged on a homemade acrylic (PMMA) base. The motor is imbedded in the acrylic base too. The function of transmission system is to transform the rotational motion of motor into a reciprocating motion.

The analysis of movement for four linkages construction is modified with JAVA software, shown in Fig. 3, *Flap design 2.2*, shared on Ornithopter zone [9]. All materials of the linkages made by MEMS fabrication technology are titanium alloy. And the acrylics are fabricated by laser machining. First linkage composed by two acrylic disc gears which could reduce vibration from deceleration system. The material of second linkage is titanium and the third linkage material is acrylic. The fourth linkage is a hollow stainless tube which connects to the acrylic base, this linkage also named ground linkage. The stroke of the flapping wing is 54 degree in angle.

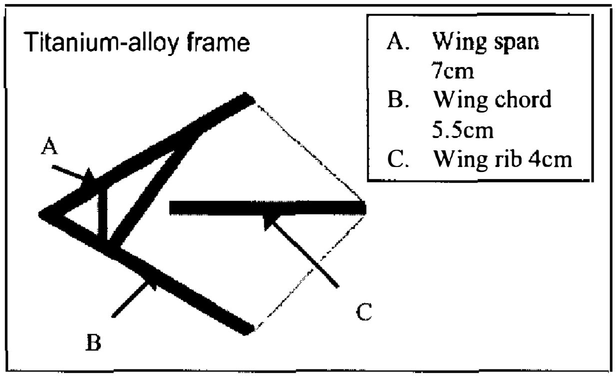


Fig. 1 Flapping-wing frame

TABLE I

Properties of Titanium grade4

TITANIUM GRADE 4	
Tensile(psi)	50,000
Yield(psi)	70,000
Hardness	RB 100

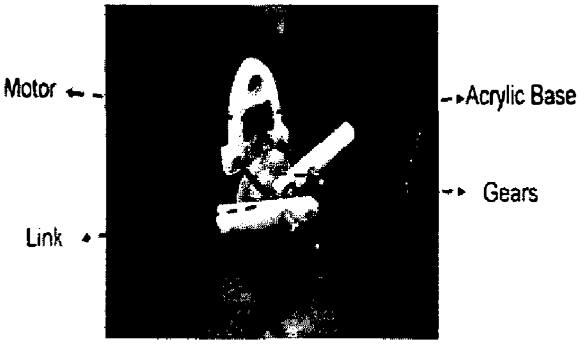


Fig. 2 Gear transmission system

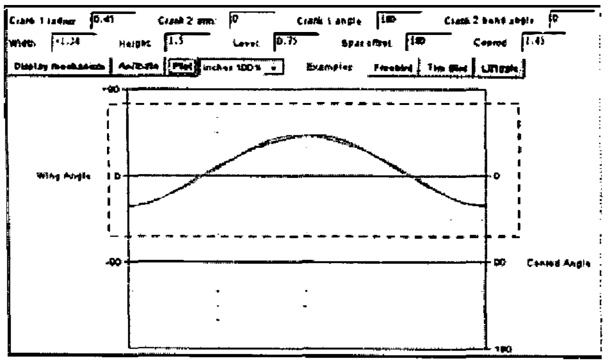


Fig. 3 *Flap design 2.2* analysis software

III. FABRICATION

The fabrication process of titanium-alloy MEMS wings flow is shown as Fig. 4:

Fig. 4(a): The titanium-alloy is cleaned with acetone and isopropyl alcohol (IPA). Then, it is flushed with de-ionized water (D.I. water).

Fig. 4(b): The titanium -alloy double sides coated with photoresist (PR), AZ4620, by a spin coating method. Exactly control the rotation speed to get 10μm thickness of PR which is used as mask layer.

Fig. 4(c): The up side PR is patterned under UV light. This step defines a pattern as an etching mask which protects titanium-alloy against etchant. Then, the mask layer is developed with a development agent, AZ400K. The residual patterns protect titanium from etching.

Fig. 4(d): The substrate is dipped in HF etchant to etch uncovered titanium for 50 minutes. After the etching process, the wing frames are formed.

Fig. 4(e): Put the substrate in acetone solution. The PR is striped from the both side of titanium-alloy surface. Then, all parts are flushed with DI water.

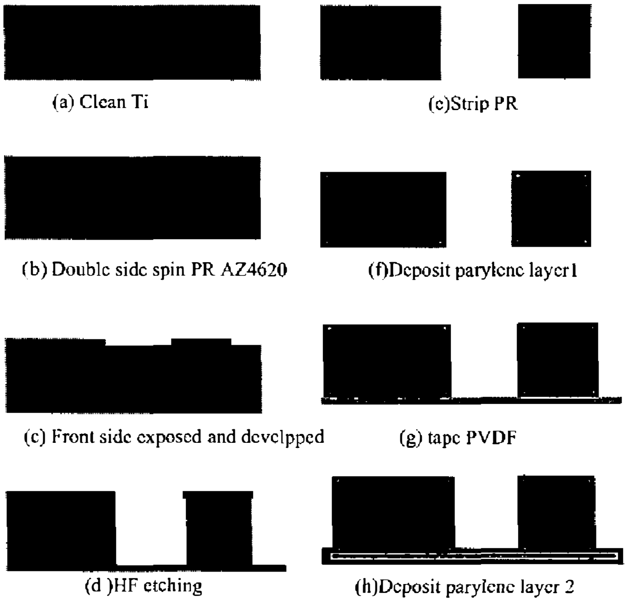
Fig. 4(f): The first parylene diaphragm deposited on titanium alloy in parylene coater. For this step, 15g of parylene dimmer yields approximately 11.5μm and this parylene is used as insulated layer.

Fig. 4(g): PVDF, a piezoelectric film, is pasted on the first parylene film.

Fig. 4(h): PVDF film and wing-frame is coated parylene. Finishing above mentioned work, we can get the airfoil of MAV, shown in Fig. 5.

The real pictures of the flapping wing and transmission system after construction are shown in Fig. 6. The transmission system is composed of linkages, a reduction gear module, stainless hollow tubes and acrylic base. The acrylic base is formed by laser machining. The stainless hollow tubes at both sides are the nodal points (ground linkage) support the reciprocating (flapping) motion. The active and driven linkages made of titanium and these parts are fabricated almost like wing frame process. One end of active linkage connects to reduction gear which propelled by a DC motor set and another end is integrated with driven linkage by a pin joint. To avoid the interference, the linkages must be placed on two different planes when they work.

The total mass of the MAV, including transmission system, wings and motor, is about 10 grams, and the details of every components constructing the MAV is shown in table II. All the parts including motor, flapping wings, gear transmission module, empennage, lithium battery and airframe are assembled successfully, and the total mass of this flapping MAV is less than 22 grams, shown in Fig. 7. The flapping action and frequency control could be effectively handled by the wireless controller purchased commercially on the shelves.



(a) Clean Ti

(e)Strip PR

(b) Double side spin PR AZ4620

(f)Deposit parylene layer1

(c) Front side exposed and develpped

(g) tape PVDF

(d)HF etching

(h)Deposit parylene layer 2

Fig. 4 Process flow of flapping wing

Fig. 5 Flapping wing with parylene-PVDF

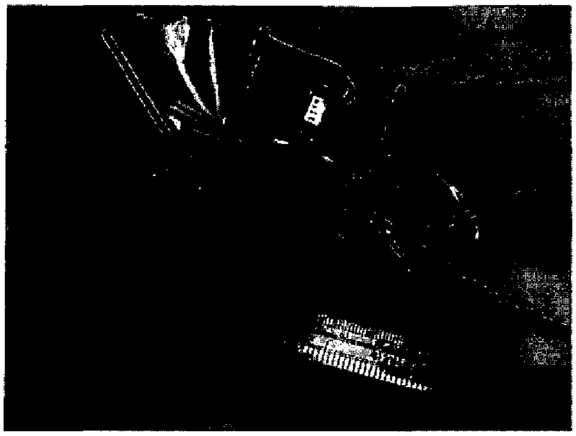


Fig. 6 Transmission system and flapping-wing

Table II
Mass of components for the MAV

Components	Weight(g)
Wing frame	1.62
Base	1.10
DC motor	4.9 (including wire)
Gear set	1.00
Acrylic linkage	0.56
Titanium linkage	0.2
Total mass : 9.38g	

Fig. 7 MAV appearance after assembling

IV. WIND TUNNEL TEST

In wind-tunnel experiment, the MAV is placed on the load-cell directly to pick up lift force information. The wind-tunnel system is shown in Fig. 8. In general, the bird flight models are classified into two types, gliding and flapping. The experiment imitates gliding of birds or fixed-wing vehicle fly in the sky. Due to the MAV mechanism could conform to the Bernoulli theory. In order to imitate bird flight in gliding state, the cambered rib forms an angle of attack in this design to generate the lift force. It is acquired from the precise load cell in wind tunnel test. The first test is to probe into the relation between the wind speed and the lift force with no flapping at various wind speed. The second test is research on the frequency of flapping relate to the lift force at various wind speed. Flapping frequency is handled by wireless controller, and the lift force values are collected simultaneously from parylene-PVDF wing and load cell. All data are collected and analyzed with the software, *InstruNet World 2.0.*

V. RESULT AND DISCUSSION

The first test result reveals approximately the lift force is direct proportion to the wind speed with no flapping, shown in Fig. 9. This could be explained that birds need initial velocity to help fly by run-up or jump from trees. The second test result shows the lift force is approximately proportion to the flapping at various wind speed (3-17 miles per hour; mph), shown in Fig. 10.

In the wind-tunnel experimental, the signals from load cell and PVDF film are acquired successfully. Both of the lift signals from PVDF and the load-cell are basically identical with the same flapping frequency and with the similar qualitative behaviors, shown in Fig. 11. However, the signal from the load-cell is somewhat vulnerable to background noise from high frequency mechanical vibration of wind-tunnel, and it justifies the more appropriate usage of our proposed on-site PVDF smart skin for MAVs. By the in-situ measurement or the smart skin technique proposed herein, we hope to purchase more bountiful unsteady aerodynamic information of MAVs in the future work. The preliminary result shows the lift force and the signals from PVDF are highly interrelated. If the trust force could also be acquired as lift force value easily with PVDF-parylene wings, it will be the similar case to get trust information from PVDF sensors. Therefore the wind-tunnel test equipment and expensive load-cell data-acquisition system might be replaced by the PVDF on-site measuring system probably.

Although, the total weight of the MAV is less than 22 gw. We still proceed to look for lighter battery to improve endurance for furthermore test. Now, the thickness of the lithium battery we used is 3mm, the size is still too big. If the thickness is down to 50μm.Maybe we could use the battery as flapping-wing

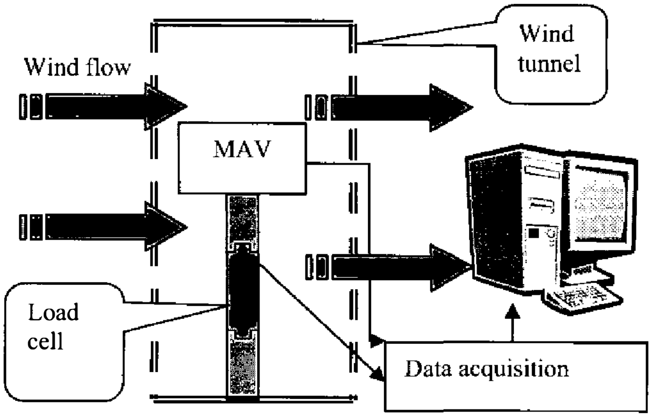


Fig.8 The wind-tunnel system

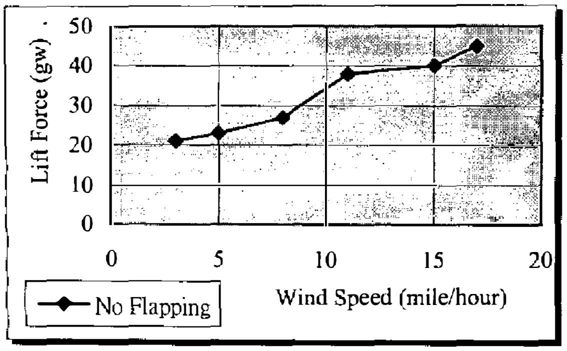


Fig. 9 Lift force and wind speed, with no flapping

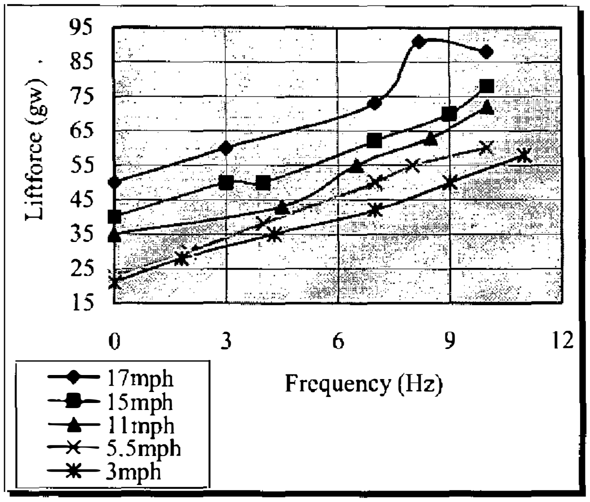


Fig. 10 Lift force and frequency with various wind speed

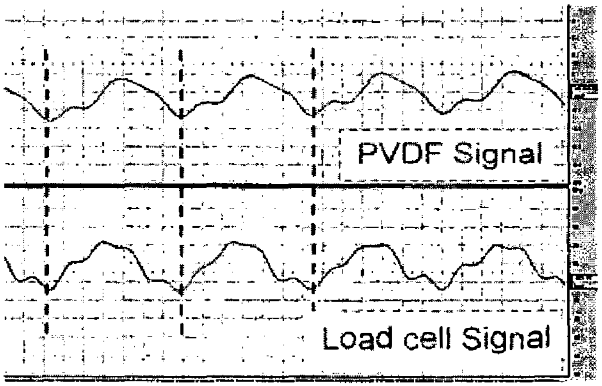


Fig.11 Signals from PVDF and load cell

VI. CONCLUSION

The parylene-PVDF flapping-wing is integrated successfully with MEMS fabrication technology. And the whole weight of the MAV including lithium batteries is less than 22 grams. In wind-tunnel experiment, the signals are on-site acquired from the load-cell and the PVDF foil at the same time and the two waveforms are highly similar. In appearance, the wind speed that MAV can bear is up to 27 kilometers per hour with no obvious deformation. The experimental result reveals the lift force is proportioned to the wind speed with no flapping situation. With increasing flapping frequency, the lift force is increased at various wind speed.

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REFERENCES

[1] S. Ashley,"Palm-Size Spy Plane," *The American Society of Mechanical Engineers*, February, 1998. pp. 74

[2]. T. Nick Pornsin-sirirak, "Titanium-alloy MEMS Wing Technology for a Micro Aerial Vehicle Application," *Sensors and Actuators A: Physical*, 2001, Vol. 89, pp. 95-103.

[3] T. Nick Pornsin-sirirak, "Flexible Parylene-valved Skin for Adaptive Flow Control," Proceedings of 15th IEEE MEMS conference, Las Vegas, USA, Jan. 20-24, 2002, pp. 101-104.

[4] http://www.artificialmuscle.com/

[5] http://fourier.vuse.vanderbilt.edu/cim/projects/crawler.htm

[6] M. Sitti, "PZT actuated four-bar mechanism with two flexible links for Micromechanical Flying Insect thorax.", Proc. of the IEEE Robotics and. Automation Conf., pp. 3893-3900, Korea, May 2001.

[7] http://www.gtri.gatech.edu/atas/teams/proj_entomopter.html

[8] T. Weis-Fogh, "Quick Estimates of Flight Fitness in Hovering Animals, Including Novel Mechanisms for Lift Production," *Journal of Experimental Biology*, 1973, vol. 59, pp. 169-230.

[9] http://parylene.com