A FLAPPING MAV (MICRO AERIAL VEHICLE) WITH PVDF-PARYLENE COMPOSITE SKIN

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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 people to investigate the unsteady aerodynamic characteristic of flapping wings. In this paper, the flapping wing of lightweight and high strength is composed of the titanium-alloy frame and the parylene skin. Such an integration of fabrication needs the help of MEMS processing technique. In the wind-tunnel test of the flapping MAV, the signals from load cell and PVDF film are used to detect the on-site lift. Both of the lift signals from PVDF and the load-cell are basically identical with the same flapping frequency and the similar qualitative behavior. Finally, we integrate Li-battery into the MAV to perform a successful free flight with a range of 10-15 meters.

1. Introduction

This research attempts to fabricate a MAV by using the mature micro-electro-mechanical-systems (MEMS) technology. The terminology of MAV, defined by Defense Advanced Research Projects Agency (DARPA), denotes the size-limitation and the performance requirements of air vehicles [1]. The total wingspan of a MAV is less than 15 cm in dimension; the highest velocity is about 48 km/hr; the range of the flight mission is about 10 km; and the flight endurance is about 20-120 minutes. According to different flying motions, MAVs can be classified into three types of air vehicles composing the fixed wing, the rotary wing and the flapping wing. Up to the recent years, many military and academic departments still supported the development of MAVs. Among the three types of MAVs mentioned above, the flapping wing is the most suitable configuration for the palm-size MAV.

The earliest flapping vehicle (or ornithopter) was made by Gustave Trouvé[2]. No ornithopter was developed by MEMS technology until the end of the last century. The least total mass of only 11.69 grams for a flapping MAV including airframe, flapping wings, an actuating motor, a remote controller and an energy supply system could be easily achieved by MEMS technology, was done by Caltech micromachining lab in 1999-2002 [3-4].

The research group in Stanford Research Institute (SRI) used piezoelectric polymer material, so called “artificial muscle”, to drive the flapping wing [5]. They transformed an electric current into a continued expand-and-contract motion to drive the flapping wing and simulated a more complex flying mechanism.

The MAV group in Vanderbilt University utilized a mature fabrication technology of a creeper driven by a piezoelectric material to simplify the mechanism of flapping wings [6]. Sitti et al. mimicked a flight motion of a fly, “Calliphora”, to produce a micromechanical flying insect (MFI) [7].

The researchers in Georgia Tech Research Institute (GTRI) took a motive force supplied by a reciprocating chemical muscle to drive a MAV with two pairs of flapping wings located on the two ends of the airframe [8]. Although the previous interesting works [2-8] of MAVs got successes of flying by wireless remote control, none of the programs has been able to achieve a long and sustainable flight. Moreover, the detailed mechanism of the flapping flight is still under dispute and the unsteady aerodynamic characteristics of the flapping MAVs are unclear and mysterious.

Therefore, in order to get more information during the flapping maneuver, this work not only measured the aerodynamic force of a homemade MAV by the conventional load cells in the wind tunnel, but also proposed the integration of PVDF (poly-vinylidene-difluoride) piezoelectric foils to the parylene flapping wings of the MAV to pick up the in-situ lift force preliminarily. We used MEMS technology to fabricate a titanium-alloy wing frame and a set of gear-reduction transmission components, and deposited conformal parylene film on the wing frame as the airfoil skin [3-4, 9]. The actuation force or torque available for the flapping wings is drained from the gear-reduction transmission set linked with a high-speed DC motor powered by commercial poly-lithium batteries. The parylene wing skin can be used as an electrical isolation layer between the PVDF...
piezoelectric sensing element and the titanium frame. The preliminary result in this paper proposes a novel approach of integrating a parylene-PVDF hybrid wing in an in-situ way to monitor the lift force of a flapping MAV in the realistic wind-tunnel test.

2. Design Concept

To obtain an accurate size of titanium-alloy airframes with no residual stress is not easy by traditional machining technology. Substantial residual stress could cause a warping deformation in the structures of airframes, and it makes the geometry of the airfoil out of control from the designed shape quite easily. Therefore, wet etching technique is accessed to tailor the airframe structures from a titanium plate with no apparent residual stress, and parylene coating technique is applied to lay the wing skin attached on the titanium frame, respectively. The followings are the design details of airframes and gear transmission systems.

2.1. Design of the titanium-alloy airframe

The primary purpose is to probe into enhancing the flapping frequency correlated to lift force at various wind speed. Higher flapping frequency always requires the larger wing loading and strong concern with structural failure. Therefore, how to design the flapping wings with high strength and low weight is indeed a crucial issue. We use matured MEMS technology for fabricating the wings to ensure the accurate size control and smartness of the flying system. The material of airframes is titanium alloy (titanium grade 4, the mechanical properties are listed in Table 1). Detail dimensions are shown in Fig. 1.

2.2. Design of the gear transmission system

The movement for the four-linkage construction of a MAV is analyzed by a JAVA software named as Flap design v.2.2 and shown in Fig. 2. By adjusting the sizes of linkages and gears, we can obtain an optimal solution of a high symmetry and smooth mechanical motion. This software can be freely accessed on the website of Ref. [10]. The first link is composed of two acrylic disc gears, which could reduce vibration from deceleration system. The second link is titanium alloy made by MEMS process, and the third link is acrylic fabricated by laser machining. The nodal point is a hollow stainless tube that connects to the acrylic base rigidly. The stroke of the flapping wing is 54 degree in angle.

The MAV deceleration system, shown in Fig. 3, composed of a gear-reduction transmission set to adjust torsion and rotational speed outputted by a DC motor. The reduction gears not only transform the rotational motion of motor into a reciprocating flapping motion, but also slow down the rotation speed of driving motor and raise higher torsion exported to flapping-wings. This deceleration rate of the gear–reduction transmission reaches 27.7. The whole gear set is arranged on a homemade acrylic (PMMA) base. The motor is imbedded in the acrylic base, too.

<table>
<thead>
<tr>
<th>TITANIUM GRADE 4</th>
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<tr>
<td>Tensile(ksi)</td>
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<td>Yield(ksi)</td>
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<td>Hardness</td>
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Fig. 1. Two types of flapping-wing frames. The thickness of Ti-alloy frame is 250µm and 2mm in width. The area of wing A and wing B are 64.50 cm² and 108.75 cm², respectively.

Fig. 2. Flap design 2.2 analysis software

Fig. 3. Gear transmission system
3. Fabrication

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

Step (a): The titanium-alloy is cleaned with acetone and isopropyl alcohol (IPA). Then, it is flushed with deionized water (D.I. water). Step (b): The titanium-alloy double sides coated with photoresist (PR), AZ4620, by a spin coater method. Exactly control the rotation speed to get 10 µm thickness of PR which is used as mask layer. Step (c): The up side PR is patterned under UV light. This step defines a pattern as an etching masking which protects titanium-alloy against etchant. Then, the mask layer is developed with a development agent, AZ400K. The residual patterns protect titanium from etching. Step (d): The substrate is dipped in HF etchant to etch uncovered titanium for 50 minutes. After the etching process, the wing frames are formed. Step (e): Put the substrate in acetone solution. The PR is stripped from the both side of titanium-alloy surface. Then, all parts are flushed with DI water. Step (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. Step (g): PVDF, a piezoelectric film, is pasted on the first parylene film. Step (h): PVDF film and wing-frame is coated with parylene.

Finishing the work mentioned above, we can get the airfoil of the MAV, shown in Fig. 5. The real pictures of the parylene flapping wing and the transmission system after construction are shown in Fig. 6.

After assembly, the total mass of the MAV, including transmission system, wings, motor, fuselage, empennage and two Poly-lithium batteries are 13.91 and 13.52 grams, respectively.

Fig. 4. Process flow of PVDF-parylene wing

4. Wind tunnel test results

In the wind tunnel testing, the MAV is placed on the load-cell directly to obtain lift and trust force data. The positive angle of attack is 20 degree of the fuselage. The wind-tunnel test system is shown in Fig. 7.

The first test is to probe into the relation between the wind speed and the lift force with no flapping at various wind speed. In Fig. 8, the test result show the wing B has higher lift force than wing A due to the wing B has a larger wing area. Both of them have the mutual tendency that the lift forces are almost increased with square of the wind speed.

Then the aerodynamic performances of the two wings were studied. The experimental result, shown in Fig. 9, the wing A is superior in generating lifts and trusts in flapping flight. Due to the wing A has stronger span wise, chord and rib, so the stiffness of flapping wing is an important issue in force generation. The lift coefficient can be expressed as follows:

\[ C_L = \frac{2L}{\rho \times A \times U^2} \]  
\[ C_T = \frac{2T}{\rho \times A \times U^2} \]

where \( L, T, \rho, U, \) and \( A \) are lift, trust, air density, flight speed, wing area respectively. The advance ratio \( J \) is the ratio of the flight speed to the speed of the wingtip. It is given by

\[ J = \frac{U}{2 \times f \times b} \]

where \( f, \) and \( b \) are stroke angle, flapping frequency,

Fig. 5. Flapping wing with parylene-PVDF

Fig. 6. The apperance of the MAVs.
and semi-wing span, respectively. In general, unsteady-state flight has an advance ratio $J$ of less than 1.

The signals from load cell and PVDF skin are used to detect the on-site lift information. Both of the two waveform are basically identical with the same flapping frequency and the similar qualitative behavior. The collected data is shown in fig. 10.

![Fig. 7. Wind tunnel test system](image)

![Fig. 8. Relation of lift-force vs. wind speed with no flapping.](image)

![Fig. 9. The lift and trust coefficients of wing A and wing B.](image)

**Conclusion**

The PVDF-parylene flapping-wing is successfully fabricated by MEMS technology. In the wind tunnel test, the flapping information is acquired simultaneously from PVDF skin and load cell on site. Experimental results reveal that the waveforms have high similarity. This result also demonstrates that the smart PVDF skin has the plentiful capability to monitor aerodynamic information of flapping. The performances of flapping wings are also studied herein. The lift force is increased almost with the square of the wind speed. In unsteady state, the wing A has higher superiority of aerodynamic performance than the wing B. It is apparent that stiffness of flapping wing plays an important position in production of lifts and trust force. The MAV were built including commercial lithium batteries are less than 14 grams.

**References**

2. O. Chanute, *Progress in Flying Machines*. (1894)