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Micro-Electro-Mechanical Flapping Wing Technology for Micro Air Vehicles

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Abstract This paper presents the fabrication and testing of a prototype micro-electromechanical (MEMS) flapping wing aerial vehicle. A flapping mechanism was developed that couples a 3cm PZT-5H bimorph actuator oscillating at 13Hz with two flexural wing joints at the distal end of the bimorph. Various bodies and wing frames of the MEMS flapping device were developed using 3D Prototyping technology. The 5cm wing span was manufactured utilizing a Fullcure820® resin as the wing frame and polyethylene as the airfoil. Joints were created at the wing root to allow for more freedom for the angle of attack of the wing. The flapping performance was experimentally investigated in terms of the flapping frequency, the stroke amplitude, the instantaneous wing force, and the power requirements. Finally, a palm sized flapping wing micro air vehicle was produced to demonstrate successful flapping.

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Introduction

Army combat operations have placed a high premium on reconnaissance missions for Unmanned Aerial Vehicles (UAVs) and Micro Air Vehicles (MAVs). UAVs and MAVs provide situational awareness that will shape the decisions of the squad command, such that these platforms are designed to be the "eyes and ears" for the soldier. One approach for accomplishing this mission is to develop a biologically-inspired flapping wing insect that can maneuver into confined areas and possess hovering capabilities. In order to execute aerial maneuvers, insects must not only generate lift to remain aloft, but they must also manipulate aerodynamic forces to steer and maneuver [1].

Significant technical strides have been accomplished in designing centimeter scale micro air vehicles (MAVs). They are of interest for limited duration electronic surveillance and sensor detection military missions [2]. Some advantages of MAVs include low noise and low radar cross section, low power consumption, and ease of generation of lift or thrust at low weight. MAVs are implemented as either fixed wing or flapping wing solutions. Fixed wing MAVs (e.g. rotors) use the wing span, the angle of attack as a function of forward airspeed, and the surface area to gain lift and thrust, meanwhile flapping wing system generate lift through the flapping wing beat frequency. A significant advantage of the flapping wing systems is that it offers lower bandwidth wherein the cyclic control inputs to maintain lift and stability operate at lower frequencies as compared to a rotor system.

It has been demonstrated that it is possible to obtain a flapping motion by coupling a polymeric wing to a distal end of a piezoelectric bimorph actuator replacing the use of motors. Piezoelectric actuators operate under the reverse piezoelectric effect, wherein an electrical current passes through the material and it undergoes strain (up to 4%). Since the piezoelectric strain is not significant enough to generate large deflection, a mechanical amplification scheme is usually devised in order to generate a considerable amount of displacement. As shown in Figure 1, a piezoelectric bimorph is constructed from bonding two plates of piezoelectric materials so that their polarizations are anti-parallel to one another when an electric field is applied across the

beam. Whereby the piezoelectric bimorph creates a bending moment, and this is accomplished when one layer expands while the other layer contracts.

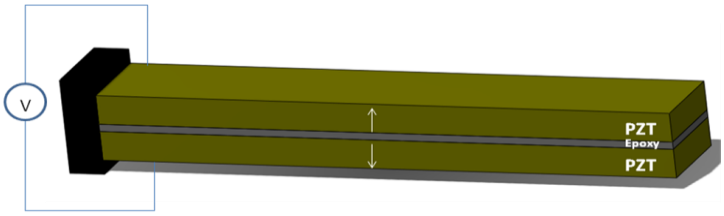

Figure 1. Conventional Bimorph Actuator

In this paper, a flapping mechanism was developed that couples a 3cm PZT-5H bimorph actuator oscillating at resonance frequency with flexural wing joints placed at the distal end of the bimorph (see Figure 2). As a result, a flapping motion is generated from operating at the fundamental resonance frequency of the system.

Figure 2 .Flapping Wing Device

Experimental

PZT bimorphs were purchased from Physik Instrumente L.P., USA, and the dimensions are 3.6 cm in length, 0.65 cm in width, and 0.075cm in thickness. Three types of wings were fabricated with low density polyethylene, Fullcure®930, and electro active polymer dimethylsiloxane. The relative thickness of each type of wing material was 20µm thick for the low density polyethylene, 200µm thick for the Fullcure®930 and 600 µm thick for the electro active dimethylsiloxane. The polymeric wing spars were made of FullCure®840 Veroblue produced from an Eden 260V 3-D printer manufactured by Objet Geometries Ltd. The peak to peak displacement was measured using a MTI-2100 Fotonic™ Sensor manufactured from MTI instruments. The flapping wing wind speed was measured with a Hot Wire Thermo anemometer by Extech Instruments Inc.

Results and discussion

The force vector for one degree of freedom was measured. The measurement of the flight forces involved measuring the moments on the wings using strain gauges. Semiconductor strain gages were bonded directly onto a stainless steel fixture in a Wheatstone bridge configuration to measure the instantaneous wing forces. In this case, measuring the strain gives the moment directly:

$$M=\frac{EI\square}{z} \qquad (1)$$

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Wherein the E is the modulus of Elasticity of the material, I is the cross sectional moment of the inertia, □ is the strain and z is the distance from the gage to the neutral axis [3]. During a wing stroke a force distribution develops along the wing spar. The force was calculated to be 30μN, which was not sufficient enough to produce lift.

It has been confirmed that this simple actuation mechanism delivers one degree of freedom (DOF). However, this bending motion does not offer enough force to give lift. So in order to increase lift, we decided to create a modified bimorph actuator design to deliver two degrees of motion. Most flying insects have over three degrees of freedom, which consist of wing angle, angle of attack, and out of stroke plane deviation [4]. In order to achieve sufficient lift, there are two mechanisms such as rotational circulation and wake capture that are employed to generate lift forces [5]. Hence, a functionally modified piezoelectric bimorph was designed to realize two degrees of freedom or motion namely the flapping and twisting facilitated by a simple actuation mechanism. Further studies are required before conclusions about the functionally modified piezoelectric bimorph can be established.

Figure 3 shows the displacement as a function of frequency. The bimorph actuator It should be noted that the 22 μm thick low density polyethylene wing material displayed the highest flapping amplitude at 11mm at 13 Hz resonance frequency at $60V_{pp}$. As shown in Figure 3, the resonance frequency yields the highest displacement. The synchronization of the spar motion, the bimorph amplification scheme, and the mechanical transmission element mandates the flapping amplitude. Insect flight of the meso scale (1-15cm range) requires both large stroke amplitude and wing rotation. Figure 4 displays the wind velocity of the low density polyethylene flapping wing by using an Extech anemometer. The distance between the trailing edge of the wing and the anemometer was maintained at 1mm for all measurements. At resonance there was also a maximum output of wind at 2.5 mi/hr. We found a direct relationship between the wing flapping amplitude and the wind velocity when the device is operated at the fundamental resonance frequency of the system.

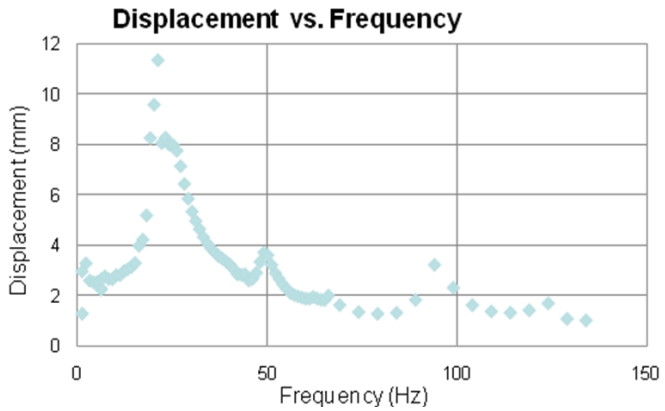

Figure 3. This graph displays displacement as a function of frequency. The displacement was measure at $60V_{pp}$.

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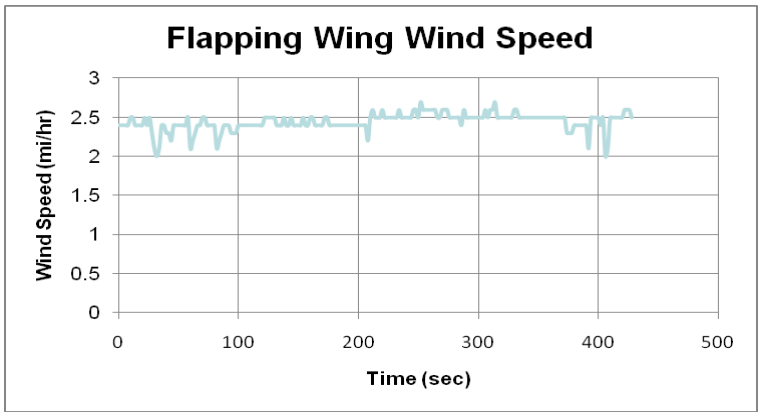

Figure 4. Flapping Wing Wind Speed measured with a Hot Wire Thermo-Anemometer

A simple electrical model of the PZT was analyzed using traditional circuit analysis techniques for power consumption. Figure 5 illustrates this model and the losses that were included. Note that R_{lossa} and R_{lossb} may both be considered losses due to the resistance inherent resistance of the PZT bimorph and solder joint as well as a dynamic resistance dependent on the force of the flapping wing. For the test bench amplifier and signal generator this was simply set to an imagined a worse case scenario and an amplifier was designed on the basis of this power draw. The amplifier for test flapping was an operation amplifier set for non-inverting amplification with a gain of 12. This amplifier was connected to a signal generator which produced a $5V_{pp}$ sinusoidal signal. Since this amplifier was connected to the PZT which is

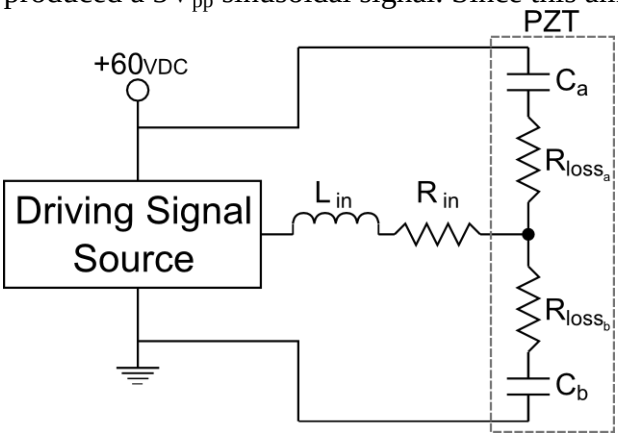

Figure 5: Wireless Power Source Schematic

an inherently capacitive load, simple inductive measures were taken to improve the signal. Utilizing this set up, measurements and experiments regarding wing composition and architecture could be performed.

Upon implementation of a non tethered flapping wing, several issues abounded. Balancing weight restrictions with power consumption issues became particularly onerous when dealing with our PZT system with relatively high voltage activation requirements. Originally

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batteries and capacitors were considered using a Cockroft-Walton generator for the DC biasing of the PZT and an RC style oscillator for the variable flapping signal. This proved to be insufficient due to voltage sag at the higher stages of the generator and the potential size of the PCB required for the circuit.

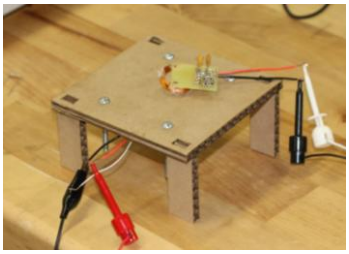

Figure 6. Wireless Power Device

A wireless approach was implemented using wireless power as outlined in [6] and [7]. Karalisa et al. implemented a simple wireless system using resonant inductors to transfer power from a base station to a detached wireless receiver [6]. To accomplish this Karalisa et al. used high Q resonating inductors in both the base station and the wireless receiver which allowed coupling at mid-field ranges. While [6] reported an efficiency of ~50%, their setup was on the order of meters in size with power on the order of hundreds of watts. To implement a wireless power system on a MAV, it would be required to shrink the size of the system to a more workable size. To decrease the size of the receiving inductor, attempts were using PCB board trace inductors. Due to the inherently low Q such inductors have losses were extreme, with almost total loss after a separation of a few centimeters. Further implementations used small air wound inductors and proved to be quite fruitful with Qs on the order of one hundred. A small system was implemented using the receiver and transmitter pictured in figure [6]. This system is to be utilized in the further development of an untethered flapping wing device.

Conclusion

We have demonstrated 11mm of one DOF of flapping motion at 2.5mi/hr flapping wing wind speeds. The preliminary lift results indicate that more work needs to be done to increase the lift and thrust of the system since the bending motion does not offer enough force to generate lift. Future work includes designing a modified bimorph actuator design to deliver two degrees of motion.

The performance of three types of wing skins was assessed and the 20μm thick low density polyethylene wing skin produced the highest flapping amplitude. We have achieved low efficiency power transfer on wireless power implementation on the order of size and weight required for implementation into flapping palm sized MAVs. Implementation of this system into an actual flapping system is in the near future. Future work includes generating smaller implementations of this wireless system as well as improving efficiency.

Acknowledgements

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