Study on piezo-electric flapping wing mechanism for bio-inspired micro aerial vehicles

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Abstract. The Micro Aerial Vehicle (MAV) with a flapping wing configuration is much more efficient and capable of generating substantial lift at low flight speeds and has excellent maneuverability. Different motor-driven mechanisms have been developed to mimic this flapping motion, but these mechanisms introduced mechanical complexity and heavy weight to the system. Piezo-electric based mechanisms have been used to solve these problems, but provide very small flapping amplitudes within the size limitation of MAVs. So some kind of amplification mechanism is needed. In this paper, a flexible wing is created by attaching a polymer skin to a pair of carbon fiber reinforced plastic spars. This wing is connected by means of an elastic-element (EE) to a pair of piezoelectric unimorphs (piezofan). The motion from the piezofan to the wing is transferred through this EE. Simulation has been done by applying sinusoidal voltages of varying frequency to this piezofan and observations have been made for the flapping amplitude of the wing for different stiffness of the EE. It is observed that the amplitude of the peak flapping amplitude initially increases, attains a maximum value, then decreases again with an increase in the stiffness of the EE. It is also observed that as the EE stiffness increases, the corresponding peak of the flapping amplitude shifts towards higher frequency.

1. INTRODUCTION

Micro Aerial Vehicles (MAVs) has gained much interest in last few years and caused a considerable work in this field. MAVs are primarily used for surveillance purpose, moreover, they can be employed in shipment, scientific experimentations and different army operations such as search and rescue, air raids etc. It is a semi-autonomous aerial vehicle that is less than 140 g in weight, measures less than 15 cm in all the dimensions and having a flying capability of 10 km distance for a time period of 2 hours [1, 2]. From the flight of the birds and insect, it has been observed that flapping flight has greater manoeuvrability and is able to generate substantial lift force at low flight speeds [3]. These MAVs typically have flight speed in the range of 30-60 kmph and operate at low Reynolds number ($10^4$-$10^5$), which are not conducive for aerodynamics characteristics [1]. The inspiration for the flapping wing structure comes from the flying insects. Wings of these insects undergo pitching, yawing and sweeping motion during the complete cycle of the wing flapping [4].

Many efforts have been made to mimic this complicated motion of flapping wing, these efforts are results in a different type of mechanism such as pneumatic and motor driven mechanism. These mechanisms have inherent drawbacks like heavy weight and mechanical complexity [4]. Piezoelectric materials have a large bandwidth, large force output, large power density and compact size, for this reason these materials are used in the smart structure as sensors and actuators [5].
materials are very useful for the flapping wing application because of the above property of these materials. But these materials have inherently very small piezoelectric effect and produce a small deflection when used as a unimorph/bimorph, so they cannot be used directly for flapping wing applications. Therefore some amplification mechanism is required to get the desired deflection. A four-bar mechanism is developed by Fearing et al. [6-7] for micro-mechanical flying insect thorax which is piezoelectrically actuated. Cox et al. [8] proposed a four-bar linkage mechanism three piezoelectrically actuated, for producing the electromechanical emulation of mesoscale flapping flight. Another flapping wing system is developed by the Syaifuddin et al. [9], which is actuated by a piezo ceramic unimorph actuator called LIPCA (lightweight piezo-composite actuator). Hsien-Chun Chung et al. [10] proposed piezoelectric fan (piezofan), which consists of two unimorph coupled with a flexible blade. This mechanism produces significant deflection and at resonance, it gives large deflection.

In the present study, a simulation model of a flapping wing is developed by introducing elastic-element (EE) between the piezofan and the wing. Simulation has been done and effect of this EE on the flapping amplitude has been observed. The simulation results shows that, this EE regulate both the peak flapping amplitude and frequency of this peak amplitude.

2. SIMULATION MODEL

The simulation model consists of two piezofans of unimorph type. They are constructed by bonding SS (stainless steel) metal shim and a piezoelectric patch together by tie constraint. Dimensions of the piezoelectric patch and SS shim are 10 mm x 10 mm x 127 µm. A couple of spars, having the property of carbon fiber reinforced plastic are attached to a polymer skin that forms the wing. This whole assembly is connected to the two piezofans in parallel by introducing an EE between them. This EE as depicted in figure 1, serves the purpose of transferring motion from piezofan to the wing. Dimensions of EE are 1 mm x 2 mm x 100 µm, and the dimensions of spars are 48 mm x 2mm x 100 µm. The gap between two piezofan is taken as 4 mm. The whole assembly of the wing is fixed at the bottom using encastre boundary condition (See figure 1).

![Figure 1. Model used in FEM simulation.](image)

3. RESULT AND DISCUSSION

The simulation model used in this paper is similar but smaller than that used by chunget.al.[10]. The material properties taken in this paper are also same and provided in table 1. The simulation is performed in two parts. The first part of simulation has been done without EE and in the second part, EE is considered.
In the first part of the simulation, a sinusoidal voltage of amplitude 170 v of varying frequency is applied to piezofan, causing the wing to vibrate. The deflection (flapping amplitude) of the wing is recorded with respect to the frequency of the applied voltage. This flapping amplitude has been compared with the literature [10] results. The two curves are given in figure 2. It is observed that as the frequency of the applied voltage is increases, the flapping amplitude of the wing also increases and after attaining a peak amplitude, it decreases as the frequency increases further. The plot due to the present work shows that the wing attains the peak of the flapping amplitude at 27.25 Hz, and the magnitude of this peak is found to be 11.11 mm. By comparing two results, it can be seen that the flapping amplitude obtained in the present work is almost half that of the literature [10]. It is also observed that the frequency corresponds to peak amplitude shifts toward higher frequency. These observations are obvious as because of the smaller size, the flexural stiffness of model will increase, ultimately resulting in a higher natural/resonance frequency of the system. For a given load, higher flexural stiffness results in lower bending deflection. Beside these, as smaller piezo-patch has been used in this work, this will leads to the smaller actuation force and eventually smaller deflection (flapping amplitude).

Table 1. Material properties and parameter used in modelling.

| Material           | PZT5H | Stainless steel | Polymer | CFRP |
|--------------------|-------|----------------|---------|------|
| Thickness(µm)      | 127   | 125            | 50      | 100  |
| Width (mm)         | 10    | 10             | -       | 2    |
| Young’s modulus (GPa) | 62    | 200            | 8       | 200  |
| Density(Kg/m³)     | 7800  | 7900           | 1534    | 1750 |
| Poisson’s ratio    | -     | 0.28           | 0.27    | 0.27 |
| d_{32} (10-12 m/V) | -320  | -              | -       | -    |
| e_{11}             | 3130  | -              | -       | -    |
| e_{22}             | 3130  | -              | -       | -    |
| e_{33}             | 3400  | -              | -       | -    |
| D_{11} (109 N/m²)  | 126   | 255.68         | -       | -    |
| D_{12} (109 N/m²)  | 79.5  | 99.43          | -       | -    |
| D_{13} (109 N/m²)  | 84.1  | -              | -       | -    |
| D_{33} (109 N/m²)  | 117   | -              | -       | -    |
| D_{44} (109 N/m²)  | 23.0  | 78.13          | -       | -    |

Figure 2. Flapping amplitude vs frequency plot without elastic-element.
In the second part of the simulation, an EE is introduced between piezofan and wing structure as shown above in figure 1. In this case simulation has been done by taking different stiffness (0.05, 0.2, 0.5, 1, 5, 10 and 50 GPa). For each stiffness of the elastic element, a 170 V voltage of varying frequency is applied to peizofan. It is observed that for a particular EE stiffness, as the frequency increases the flapping amplitude also increases and attains a peak amplitude. A further increase in the frequency leads to a decrease in the amplitude of flapping. The plot for flapping amplitude with EE is shown in figure 3. The plot shows that as the EE stiffness increases, the frequency corresponds to peak amplitude shifts towards the higher frequency. It can be seen from figure 3 that the peak frequency corresponds to different EE stiffness values (0.05, 0.2, 0.5, 1, 5, 10 and 50 GPa) are 3.95 Hz, 7.4 Hz, 12.65 Hz, 15 Hz, 23 Hz and 25.20 Hz respectively. When the EE stiffness increases, the peak amplitude first increases and starts decreasing after attaining the peak amplitude. The peak amplitude corresponding to different EE stiffness values (0.05, 0.2, 0.5, 1, 5, 10 and 50 GPa) are 8.20, 11.50, 15.0, 21.42, 12.16, 12.07 and 9.66 mm respectively. By comparing the flapping amplitude obtained with and without EE from figure 2 and figure 3, it is found that the flapping amplitude with EE stiffness value 1 Gpa is almost double that of the without EE case. It is also higher than the reference [10] flapping amplitude.

4. CONCLUSION

In this paper, a FEM model of flapping wing is developed. This model has mainly three parts, (1) the wings, (2) the piezofan and (3) the elastic-element. All three parts assembled together to form complete wing structure. The piezofan provides actuation of the wing. The motion from the piezofan to the wing part is transferred through the EE. The simulation has been done. A sinusoidal voltage of 170 v is applied to the piezofan of varying frequency. The complete simulation has been done in two parts (1) without EE and (2) with EE. In both cases variation of flapping amplitude is observed as a function of applied voltage frequency. In the first part, the simulation is performed without changing any properties while in the second part seven different simulation are performed with seven different EE stiffness. The results of both part have been compared. These results also compared with the results of literature. Two main conclusions can be drawn from this study

1. This study suggests that, reduction in the flapping amplitude due to reduction in the size of overall wing structure can be compensated by incorporating EE in the structure. This will be helpful in managing the size constraints without compromising the flapping amplitude.
2. The frequency corresponds to peak flapping amplitude can be adjusted/regulated by changing the EE stiffness. This aspect provide wide spectrum of operation of MAVs.
3. Hence this study will be beneficial in the development of economical flapping wing type MAVs with its size constraints.

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