

Development of Electromagnetic Flap Actuator for Flow Control Application

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Abstract

An electromagnetic flap actuator was developed for flow control application. The flap actuator has a deflection varied from +0.3 to -0.4 mm when DC of ± 1.0 A is applied, and the resonant frequency is about 1.0-1.2 kHz.

Keywords: Electromagnetic, MEMS flap actuator, Flow control

1. Introduction

In the last decade, researchers in fluid mechanics look into micro actuators as potentially effective and efficient control systems for applications in micro and macro flows. It is not straightforward to develop such actuator based on conventional MEMS technologies since actuators for flow control often simultaneously require large deformation, fast response, low energy consumption, and robustness in harsh environment.

One of the flow control devices that have been widely investigated is a synthetic jet actuator (e.g., Glezer et al. [1]). It has an oscillating mechanism in the form of an oscillating diaphragm mounted beneath a cavity with orifice as shown in Fig. 1. With this configuration, micro actuators used as the oscillating mechanism are protected inside the cavity, and are not directly exposed to the environment. Past studies have already demonstrated that the synthetic jet actuator operates effectively in jet vectoring [2], flow separation control [3], and thermal management [4].

For the synthetic jet actuator, velocity of the flow through the orifice mainly depends on a sweeping volume and the frequency of the oscillating mechanism [5]. To achieve a synthetic jet actuator that can be used in a wide range of applications, the oscillating mechanism with large deformation and high resonant frequency is then required.

Some of the past works [6-7] have employed PZT as an oscillating mechanism. Although PZT can be operated at very high driving frequency, it can produce relatively small deformation comparing to its bulky shape.

Our motivation is to develop efficient MEMS actuator having large deformation and high resonant frequency for the synthetic jet actuator. For this purpose, we employ

electromagnetic as the actuation principle, which provides large deformation at the cost of high heat loss.

2. Design and Fabrication

Electromagnetic actuator employed in this study is in a flap configuration, like a cantilever beam, as shown in Fig. 2. The flap with a patterned copper coil is elastically bent by the electromagnetic force acting on the copper coil due to the flowing current and a cylindrical permanent magnet placed underneath. Our design is based on the research of Suzuki et al. [8], but in this study the hollowed section is ignored to increase flap's stiffness and resonant frequency.

Materials for the flap and coil are polyimide Pi and copper Cu, respectively. The two-layer sheet of Pi with the thickness of 25 μm and Cu with the thickness of 35 μm is available. To pattern the Cu square coil with 300- μm width on the Pi flap, MEMS fabrication processes are required. According to the small cylindrical permanent magnet, the 3,500-Gauss magnet is available.

The effects of the flap's width and length to the deflection displacement and resonant frequency are investigated using electromagnetic force and composite beam models. With the configuration shown in Fig. 2, the electromagnetic force exerting on the coil is approximated as

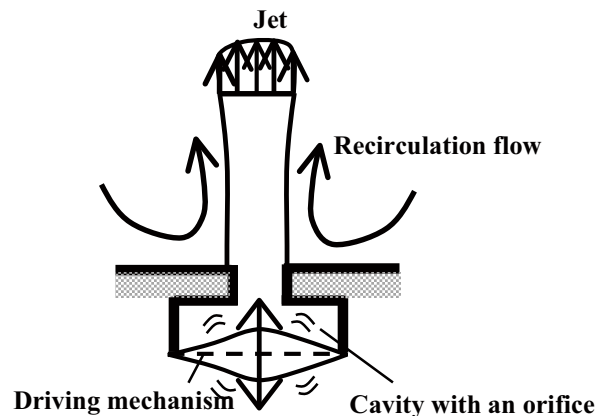


Figure 1. A diagram of the synthetic jet actuator.

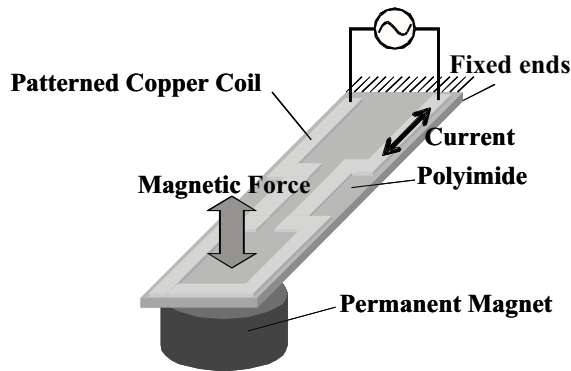


Figure 2. Diagram of electromagnetic flap actuator.

$$F = iBl, \quad (1)$$

where i is the electric current, B is the magnetic field, and l is the effective coil length. Since the deflection remains small, the magnetic field is assumed to be constant at any distance from the permanent magnet. In addition, the effective coil length is approximated to the perimeter of the permanent magnet.

Deflection of the composite flap is calculated using a cantilever beam model as shown in Fig. 3, and it is approximated to [5]

$$y = L^3 F / 3(E_p I_p + E_c I_c), \quad (2)$$

where y is the deflection of the flap tip, L is the distance from the fixed end to the center of the coil, E is Young's Modulus of materials, and I is the moment of inertia of each section. Subscripts p and c are Pi and Cu, respectively. Young's modulus of Pi is equal to 3.0×10^9 N/m² and that of Cu is equal to 12.98×10^{10} N/m².

Resonant frequency of the composite flap is also given as [5]

$$f_{res} = \frac{1}{2\pi} \frac{\lambda^2}{(L + W/2)^2} \sqrt{\frac{E_p I_p + E_c I_c}{\rho_p A_p + \rho_c A_c}}, \quad (3)$$

where λ ($=1.875$) is the vibration coefficient in air, ρ is the density, and A is the cross-section area. The density of Pi and Cu are equal to 1.42×10^3 kg/m³ and 8.96×10^3 kg/m³, respectively.

Figures 4a and 4b show the estimated deflection of the flap for various flap's widths and lengths when the current of 0.5 and 1.0 A are applied. For the case of 0.5 A (Fig. 4a), the deflection increases with the increment in length when the width is kept constant. On the other hand, for any flap's length, the deflection increases with the increment in flap's width until a maximum value. When the width is increased beyond that value, the deflection starts decreasing. It shows that the increment of width has two counter effects. When the width is small, the moment of inertia is small, but the magnitude of electromagnetic force is also small leading to a small deflection. When the width is large, although the electromagnetic force is large, the moment of inertia is also large and the deflection becomes small.

For the case of 1.0 A (Fig. 4b), the similar trend is obtained, and the deflection becomes twice that of 0.5 A.

Figure 5 shows the resonant frequency of the flap at various widths and lengths estimated by Eq. 3. From Eq. 3 and Fig. 5, it can be seen that the width has relatively smaller effect on resonant frequency than the length. For a fixed length, the width can increase, e.g., by a factor of four, without affecting the resonant frequency too much (e.g., decrease by approximately ten per cent). On the other hand, for a fixed width, small decrement of the length can cause significant increment of the resonant frequency.

In the experiments, we have fabricated the flap with the dimensions of 3×6 mm² in order to obtain both large deflection and high resonant frequency. Based on the computational results, this flap should have the deflection of about 0.6 mm at the current of 1 A and the resonant frequency of about 360 Hz.

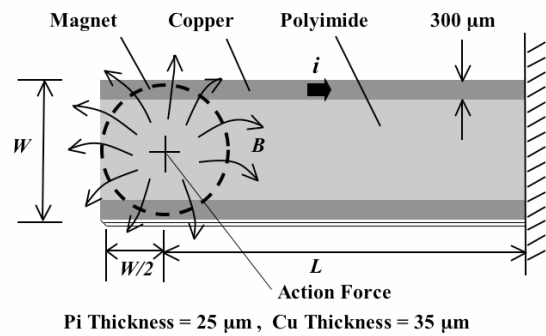


Figure 3. Flap model using for estimating the deflection and the resonant frequency.

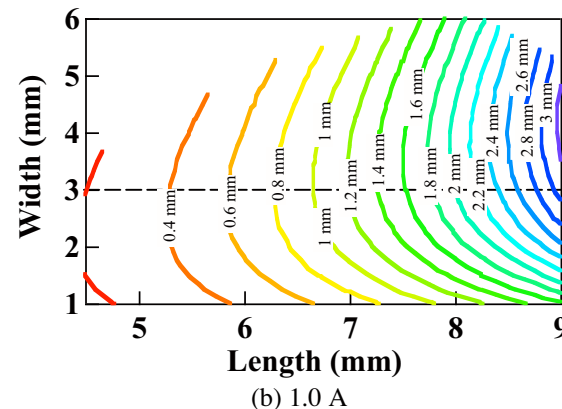
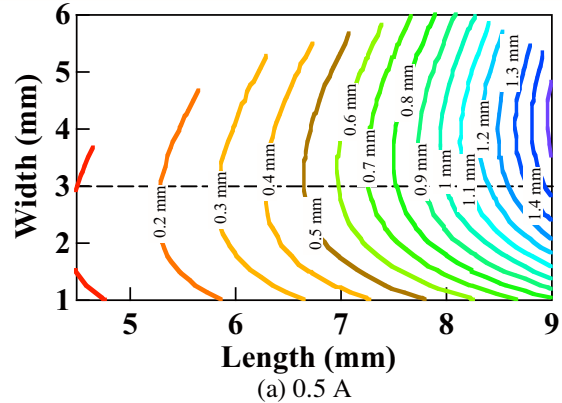


Figure 4. Estimated deflection of the designed flap at the current of 0.5 and 1.0 A.

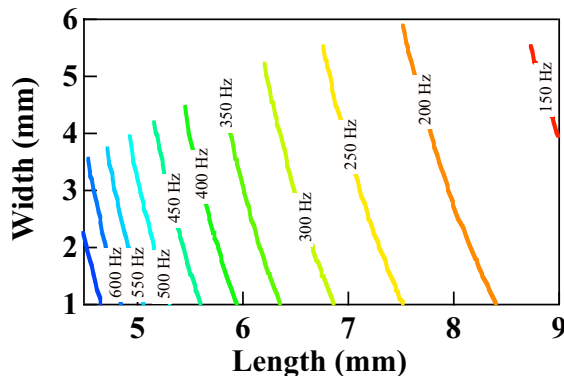


Figure 5. Estimated resonant frequency of the designed flap.

The fabrication process of the micro coil starts with a coating of photoresist dry film on the Pi-Cu sheet following by a patterning of the photoresist. Then, the Cu square coil is formed with ammonium hydroxide etching at 40 °C for 6 min. After post-processing, the Pi-Cu sheet is cut into an individual flap.

After fixing one end of the flap to a surface with acrylic glue, a set of wires is soldered onto Cu pads. To protect the connection, an insulating silicone is successively coated onto the pads.

Figures 6a and 6b respectively show the flap and its assembly with the permanent magnet. The current minor problem is the bending of the beam due to internal stresses. The flap tips are measured to stay above a surface about 0.5-0.8 mm at its neutral position.

3. Experimental Results

Static and dynamic responses of three electromagnetic flap actuators are examined. All actuators have the same dimensions, but small defection on the flap's shape may be induced in the assembling processes.

3.1 Static Response

Static deflection when applying constant DC is measured by imaging. Images of the actuator before and after applying DC are taken with a high-resolution digital camera. Two images are compared and the deflection displacement is calculated. With this system, the measurement accuracy is approximately $\pm 25 \mu\text{m}$.

The relation between the actuator's deflection and the applied current is shown in Fig. 7. From its neutral position, the actuator can deflect in both directions depending upon the direction of the current. The deflection is considered positive when the actuator deflects away from the magnet, and vice versa. From the figure, it is found that, as the actuator deflects away from the magnet, the sensitivity decreases and the deviation of the measured deflection from the predicted value given by Eq. 2 increases. This gives an indication of the effect of decreasing electromagnetic field as the actuator moves away from the magnet. The deflections at DC of -1.0 and $+1.0$ A are approximately -0.4 and $+0.3$ mm, respectively.

3.2 Dynamic Response

Dynamic deflection is examined when sinusoidal AC of ± 0.4 A is applied. Capacitance probe with the sensor

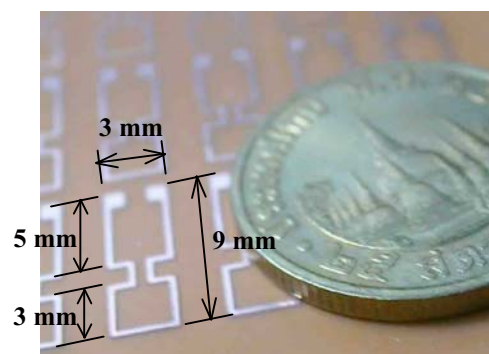
size of 3 mm is used to measure the averaged deflection in the distance range of $500 \pm 250 \mu\text{m}$ from the probe tip. Its output signal is transferred to an oscilloscope and compared with the driving voltage signal to measure lag time. For the current system, the resolution of the deflection is $\pm 2.5 \mu\text{m}$ and that of the lag time is ± 0.04 ms.

Figure 8 shows gain and phase lag of the three actuators. Gain is defined as the dynamic deflection at a driving frequency normalized by that at 30 Hz, while phase lag is the lag angle of the deflection signal from the driving voltage signal.

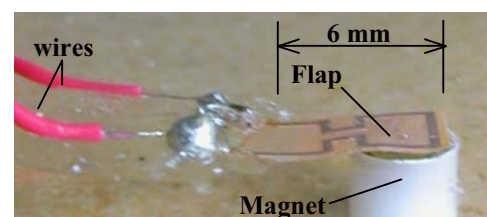
Gain of all three actuators gradually increases when the driving frequency is increased until the frequency reaches 800-1,000 Hz., at which it increases more rapidly to 8-10. After that, it decreases. The phase lag also gradually decreases to -0.2π at the frequency of 800-1,000 Hz. It then becomes out of phase ($-\pi$) with the driving voltage at the resonant frequency of about 1.0-1.2 kHz. However, this resonant frequency is twice that given by Eq. 3. This can be due to the deviation of the flap from the cantilever beam model's configuration.

4. Conclusion

Electromagnetic flap actuator was developed and fabricated with MEMS technologies as an oscillating mechanism for a synthetic jet actuator. The flap actuator, has dimensions of $0.025\text{mm} \times 3\text{mm} \times 6\text{mm}$, consists of the polyimide sheet and the copper square coil aligning on a cylindrical permanent magnet. The actuator has a deflection varied from $+0.3$ to -0.4 mm when DC of ± 1.0 A is applied, and the resonant frequency is about 1.0-1.2 kHz.



(a) Image of flap before assembling.



(b) Arrangement of flap and magnet.

Figure 6. Enlarged images of the electromagnetic flap actuator.

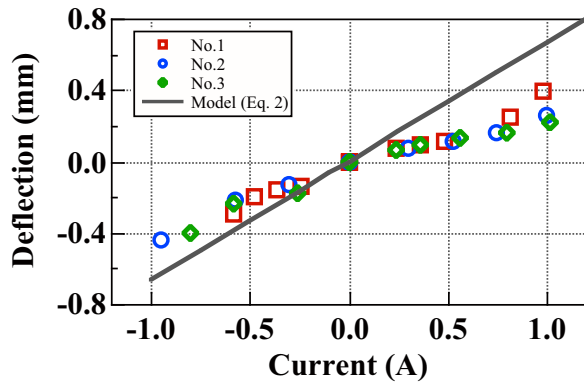


Figure 7. Static response of the developed actuator.

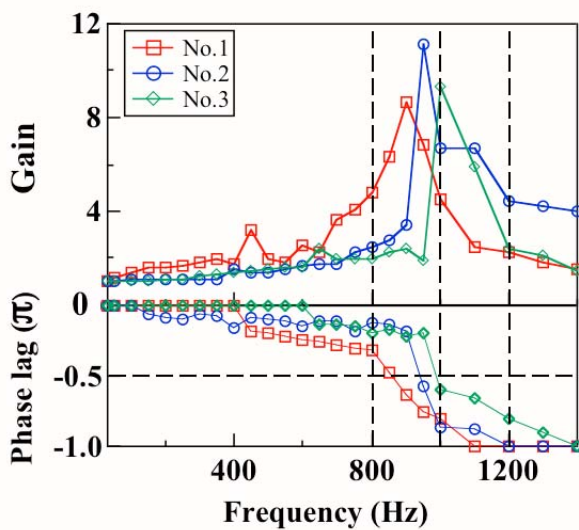


Figure 8. Gain and phase lag when driven by sinusoidal voltage.

Acknowledgments

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