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Micro Mobile Robots using Electromagnetic Oscillatory Actuator

Bu Hyun Shin and Seung-Yop Lee

***Abstract*—In this paper, we propose a compact electromagnetic oscillatory actuator and its applications to three different micro robots such as tadpole robot, 2-legged robot and 4-legged robot. The electromagnetic oscillatory actuator has a simple structure composed of cores and coils. The oscillatory motion of the actuator is theoretically analyzed. Based on the dynamic modeling and FEM simulation, a prototype is designed and manufactured. Finally, we evaluate the performance of the three types of micro robots using the electromagnetic actuator through experiments.**

I. INTRODUCTION

Recently, there have been many studies concerning micro robots for medical or industrial applications. Many researchers have developed micro robots by adopting various types of actuators. However, most of small-sized actuators do not provide enough power required for robot applications, as compared with biological living systems.

Piezoelectric actuators have strengths such as fast response, high moving speed and size reduction, but it requires high input voltage and additional structures to realize satisfactory stroke performance because of its small deformation. Various micro robots using piezoelectric actuators have been developed such as inchworm robot[1], three legged robot[2], ambulatory robot HAMR[3], myriapod robot[4], fly robot[5] and fish robot[6,7].

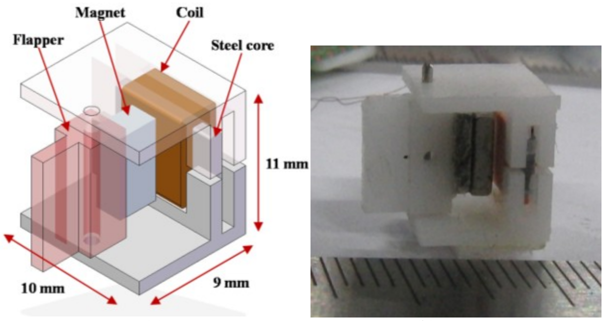
SMA(Shape Memory Alloy)actuators have advantages of a simple structure and reasonable force, however low speed and slow response are its drawbacks. Some researchers have developed micro robots using SMA actuators such as hexapod robot RoACH[8], inchworm robot[9,10], Omegabot[11], rolling robot GoQBot[12], fish robot[13,14] and glider[15].

Recently, soft polymer actuators have been widely researched. The typical polymer actuator uses IPMC(Ionic Polymer Metal Composite). The IPMC actuator has a large bending displacement and low input voltage and mobility in underwater. However, it has the disadvantages like low power and reduced bending displacement in air. Various actuators such as tadpole robot[16], fish robot[17-19], legged robot[20] and wormlike robot[21] were developed using IPMC.

Electrostatic actuators are widely used in MEMS(micro electro mechanical systems) because it is possible to reduce size using microfabrication processes. A few researchers have applied the electrostatic actuator for robotic applications such as walking robot[22] and fish robot[23].

Electromagnetic actuators have a lot of advantages such as fast response, simple control law and low cost. Rotary electromagnetic motors generally are not suitable for micro robots because most micro robots require oscillating or reciprocal motions. Mobile robots using rotary electromagnetic motors like mini-Wheg robot[24], fish robot[25] and dragonfly toy robots[26] have high mobility, but they have bigger size than other types of micro robots. The linear electromagnetic actuators are used for inchworm robots[27-30]. However, the other types of robots like legged robot and fish robot are rarely studied using electromagnetic actuators.

In this paper we propose a compact electromagnetic oscillatory actuator with a simple structure and apply the actuator to three different micro robots. The dynamic model of the actuator is theoretically analyzed. Finally, we manufacture prototypes and evaluate the dynamic performance of the three types of micro robots such as tadpole robot, 2-legged robot and 4-legged robot.



(a) (b)

Fig. 1. (a) Design modeling of the proposed oscillatory actuator, (b) the manufactured prototype

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II. ELECTROMAGNETIC ACTUATOR MODULE

A. Design

We have designed and manufactured the compact electromagnetic oscillatory actuator as shown in Figure 1. The coil surrounds the steel core. The magnet is attached the flapper. The direction of the magnetism is perpendicular to the coil in order to change the direction of current induced to the coil and oscillate the flapper.

Overall size is 10 x 11 x 9 mm (width/height/depth). The total mass is 1.5g. The magnet is rare earth magnet, ND35. The coil has 820 turn and the resistance of 58 Ω. The frame of flapper is made of ABS plastic using machining processes, and the axis of the flapper is made of steel pin. All parts are assembled by instant glue. The oscillatory angle is limited to 30 degrees by the groove of frames.

B. Dynamic Modeling

There are two types of forces applied to the oscillatory actuator. The magnetic force between the magnet and the steel core holds the flapper on the central position. That magnetic force is called as reinstating force. The electromagnetic force generates the oscillatory motion when the current is applied to the coil. The oscillatory direction is controlled by the direction of the current of the coil. The dynamic model is similar to that of DC motor because the actuator system is theoretically based on DC motor. The equation of the dynamic model is written by .

$$J\ddot{\theta} + F_{magnetic} = F_{elecromagn\ etic} \tag{1}$$

Here J is inertia and $\ddot{\theta}$ is angular acceleration. Actually the magnetic and electromagnetic forces $F_{magnetic}$ and $F_{electromagnetic}$ are nonlinear. If the proposed system is assumed to be linear, the two forces are written by equations (2) and (3).

$$F_{magnetic} = K_m\ \theta \tag{2}$$

$$F_{elecromagnetic} = K_t\ I \tag{3}$$

Here θ is rotation angle and K_m is reinstating constant which is the same as the spring constant. K_t is the torque constant and I is current. If inductor component in electric circuit is ignored, the circuit equation is written by

$$V = R\,I + K_e\ \dot{\theta} \tag{4}$$

Here V is voltage, R is the resistor of coil, $\dot{\theta}$ is angular velocity and K_e is the back-emf constant. Generally the back-emf constant is the same value as the torque constant in the case of DC motor. By combining equations (1) and (4), we obtain the second-order linear system (5) where input is voltage and output is rotational angle.

$$\frac{\Theta}{V} = \frac{1}{\dfrac{JR}{R}s^2 + K_e\ s + \dfrac{K_m R}{K_t}} \tag{5}$$

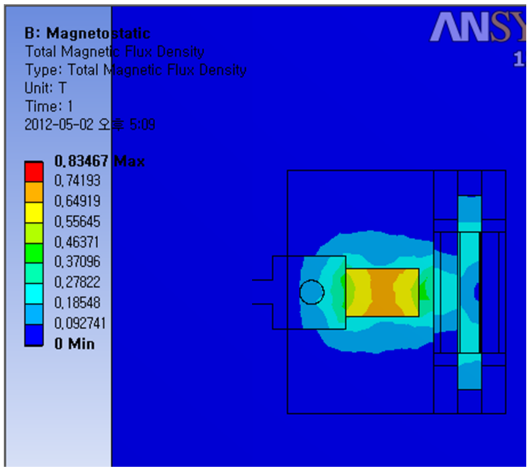

Fig. 2. Simulation result of magnetic flux density of 1-DOF oscillatory actuator using ANSYS

To estimate the performance of the oscillatory actuator, the physical parameters such as J and R are to be measured. The reinstating constant and the torque constant are calculated from FEA simulation and measurement data.

The FEA simulation result of magnetic flux is shown in figure 2. A commercial program (ANSYS Workbench) is used for the FEA simulation. The force is measured using load cell (CAS^{tm} PW4M C3). The experimental setup is shown in figure 3. The magnetic force at each angular position of the flapper is simulated and measured to calculate the reinstating constant. The electromagnetic force by the current of coil is simulated and measured to calculate the torque constant at the central position of the flapper. The obtained parameters are shown in Table 1. All the results are linearized, and the coefficients of correlation are over 95% in all cases. The maximum torque is 0.686 mNm at 7V.

TABLE I
PHYSICAL PARAMETER

Parameter		Value
Inertia (J)	Measured	$3.3*10^{-9}$ Kg/m^2
Resistor (R)	Measured	58 Ω
Torque constant (K_t)	Measured	5.68 mNm/A
	Simulated	4.15 mNm/A
Reinstating constant (K_m)	Measured	0.59 mNm/rad
	Simulated	0.57 mNm/rad

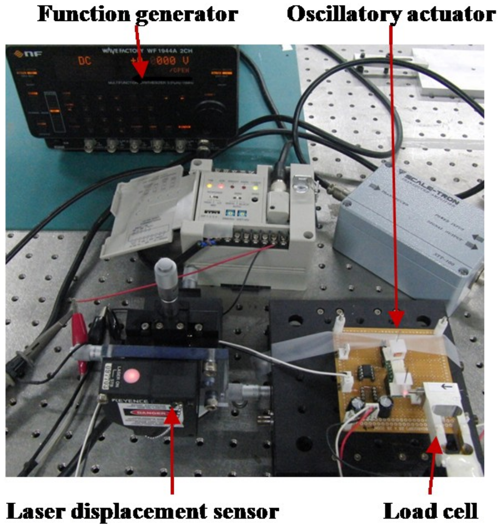

Fig. 3. Experimental setup of the oscillatory actuator

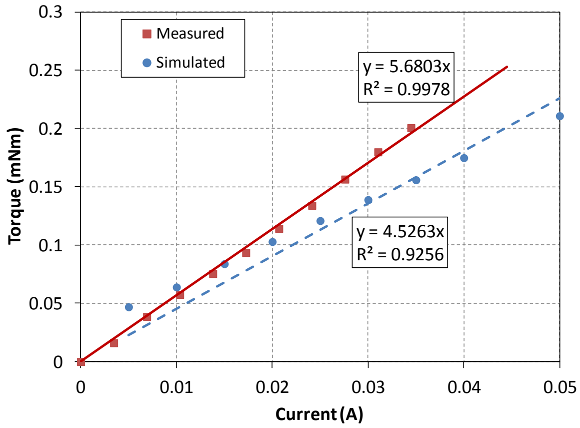

Fig. 4. Torque vs. current of the oscillatory actuator

C. *Prototype*

The prototype of the oscillatory actuator is shown in figure 1(b) and the dynamic response is measured using a laser displacement sensor (Keyence^{tm} LB 081) and function generator. The results of dynamic response are shown in figure 5. The experimental result is plotted in solid line. Results using simulated parameters and measured parameters are green a dot line and blue dash line, respectively. Results of the dynamic modeling in previous section are similar to experimental results using the prototype. The resonance frequency is 60 Hz in the experiment and 65 Hz in the dynamic modeling. The bandwidth is 85 Hz in the experiment and 100 Hz in the dynamic modeling. Based on the experimental results, the oscillatory actuator is suitable for micro mobile robots. The proposed mobile robots use the resonance of the actuator to maximize the moving speed.

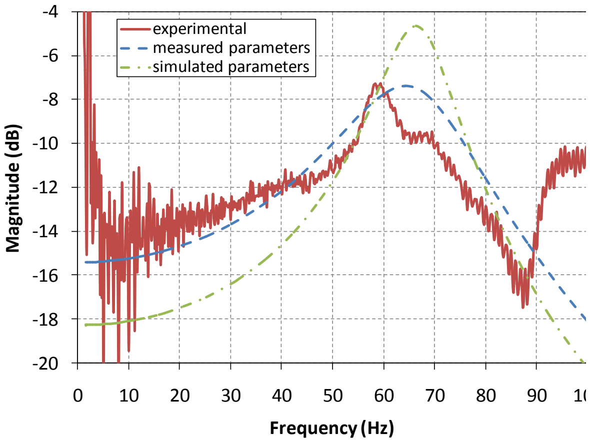

Fig. 5. Dynamic response of the oscillatory actuator

D. *Control driver*

The control driver is developed using a 8-bit microcontroller (PIC 12F675) and a power op-amp (TLV 4112). The power op-amp TLV 4112 has the size of 3 mm × 3 mm and the supply voltage of 7 V and output current over 300 mA. The control driver is designed to regulate two actuators. In this experiment we have used the power op-amp and function generator. We plan to develop autonomous robot using the developed controller and a small sized battery in the future.

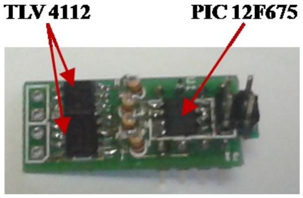

Fig. 6. The control driver using microcontroller and op-amps

III. TADPOLE ROBOT

Firstly, we develop a tadpole robot using one oscillatory actuator module as shown in figure 7. A tale is attached the flapper. The speed of the tadpole robot is affected by the shape, length and thickness of the tale. We choose the trapezoidal fin as the shape of the tale. The length is 25 mm that is twice of the oscillatory actuator. We make two tales with thickness of 100 and 200µm. The material of the tale is acryl coating film.

We implement experiments using the tadpole robot in water to measure the moving speed of the tadpole robot. The rectangular type input signal of ±3V is applied by power op-amp driver using the function generator. The robot is supplied from outside power source through enamel-coated copper coils with 20 μm. The coil is too thin to interfere with the motion of the robot. The scale is located beneath the water tank to measure the moving distance of the tadpole robot. The camera takes the video of the robot from top of the water tank. The speed is measured twice using a video camera with 60 frame per second. The average speed of the tadpole robot is shown in figure 8. The maximum speed is about 50 mm/s at 20 Hz using the tale with the thickness of 100 μm. Then the tale shows the undulated motion. It is well known that the undulated motion of the tale is efficient to increase speed[15].

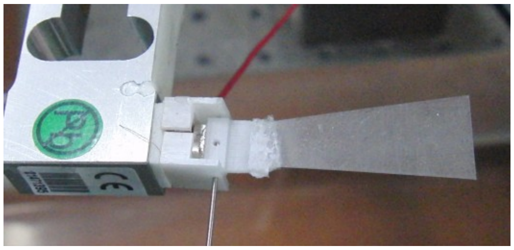

Fig. 7.Tadpole robot using the oscillatory actuator

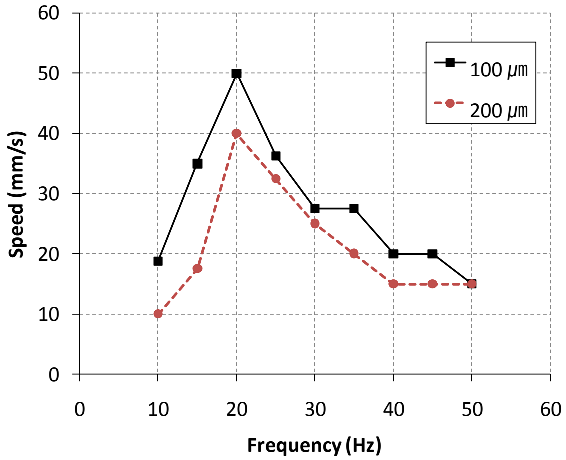

Fig. 8. Tadpole robot using the oscillatory actuator at 3V

IV. 2-LEGGED ROBOT

Secondly, we develop the 2-legged robot using two oscillatory actuators as shown in figure 9. The flappers support the frames, and the walking mechanism of the 2-legged robot generates the stick and slip motions. Two-step mechanism generates the forward motion. Firstly the flapper moves forward quickly with a sufficient torque to overcome the friction force, then the body holds the position. Secondly the flapper moves slowly in backward motion with the small torque not to overcome the friction force, then the body has the swing motion forwarding on the pivot of the end tap of the flapper. Finally, the 2-legged robot can move back and forth.

The saw type input signal of ±4V is applied by the power op-amp driver using the function generator. The speed of the 2-legged robot is affected the friction between flapper and floor. Figure 10 shows the average speed of the 2-legged robot at 4 V on the floor of paper. The maximum speed is 82 mm/s at 55 Hz.

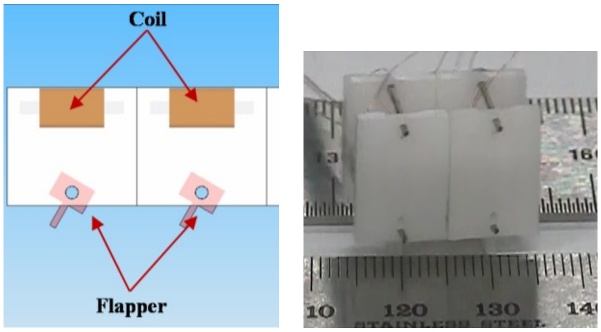

Fig. 9. 2-legged robot using the oscillatory actuator

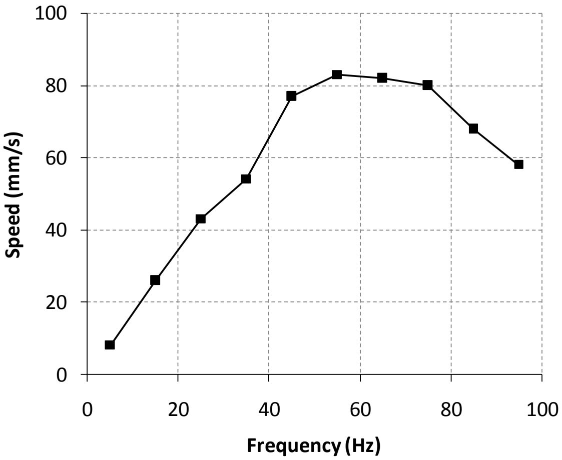

Fig. 10. 2-legged robot using the oscillatory actuator at 4V

V. 4-LEGGED ROBOT

Finally we manufacture the 4-legged robot using four oscillatory actuators as shown in figure 11. The walking mechanism of 4-legged robot uses the vibrating slide. For forward motion, the front actuators remain stationary while the back actuators oscillate back and forth simultaneously. The 4-legged robot can move the bi-directional motions. The 4-legged robot changes the moving direction if only one actuator oscillates back and forth.

The rectangular type input signal of ±7 V is applied by the power op-amp driver using the function generator. Figure 12 shows the average speed of the 4-legged robot at 7 V. The maximum speed is 48 mm/s at 75 Hz.

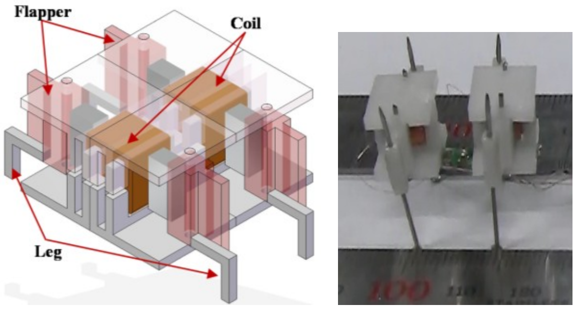

Fig. 11. 4-legged robot using the oscillatory actuator

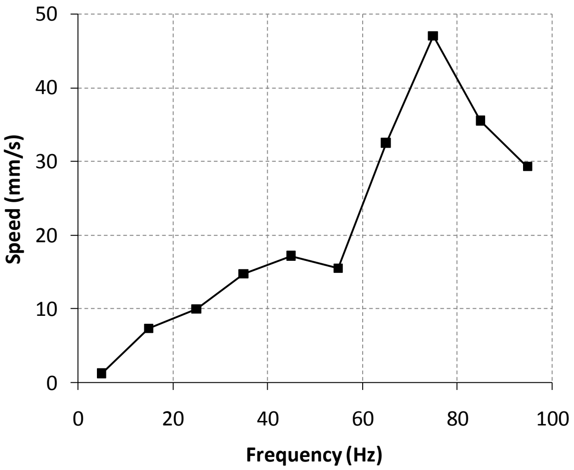

Fig. 12.4-legged robot using the oscillatory actuator at 7V

VI. CONCLUSION

We have developed the electromagnetic oscillatory actuator module and three different micro robots such as tadpole robot, 2-legged robot and 4-legged robot are implemented base on the actuator module. The dynamic modeling, simulation and experiment of the prototype are conducted. The results of the dynamic response show the oscillatory actuator module has sufficient performance for micro mobile robot. We measured the moving speed of the three micro robots from experiments. It is noted that the developed oscillatory actuator module is suitable for the actuating mechanism of many micro mobile robots.

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