Electromagnetic Linear Actuator providing High Force Density per Unit Area without Position Sensor as a Tactile Cell

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A novel, very small linear actuator that can realize high force density per cross section without position and force sensors is proposed. This actuator is used in a two-dimensional tactile display, which consists of many small one-dimensional actuators with position and force controllability. The proposed actuator has 3 layer stators, and can achieve a high electro-magnetic force. As a result, a force density of 4 mN/mm^2 is obtained with a cross section of $4 \text{ mm} \times 4 \text{ mm}$ and a moving stroke of 1 mm.

Keywords: actuator, tactile display, haptics

1. Introduction

A tactile sensor is considered to be used as a next generation human interface for mass media after visual and audio sensations are matured. The literatures of this research field have been rapidly increased depending on development of position and force research^{(1)–(4)}. These are mainly concerning one-dimensional tactile actuation. Recently, device oriented researches for transmission of two-dimensional tactile sensation have been also conducted in various fields^{(5)–(11)}. For transmission of tactile sensation, it is necessary to simultaneously transmit position and force information⁽¹⁾. Depending on difference in speed of information transmission and the volume of tactile actuator there are approximately two types of applications. One is, for example, a Braille device for blind people⁽¹²⁾⁽¹³⁾ which controls only the positions of dotted points with an open loop, and it can recognize characters by 9 dotted position information. The speed and volume of information in this field is low. Another application is concerning a two-dimensional tactile display, which needs fast and accurate control of the position and force⁽⁵⁾⁽⁶⁾⁽¹⁴⁾. Hereafter, this paper focuses on the actuator aiming at realization of a two-dimensional tactile display. The smallest device that can achieve fast and accurate position and force control in high responsiveness is required for a cell element of tactile sensor and this is defined “tact-cell” in this paper, which should be a small and compact enough for this purpose. Figure 1 shows one example of the illustration of tact-cell’s. The piezoelectric bimorph actuator utilizing the piezoelectric effect was proposed⁽⁷⁾ in which the shape is deformed by applying a voltage. The structure is a board shape for increase of the deformation. Thus, it is difficult to arrange it into the plane shape as shown in Fig. 1. The SMA

Fig. 1. Illustration of 6×6 tact-cell's⁽⁶⁾

film actuator was proposed in (8) that uses the shape memory effect in which the original geometrical shape comes back when the temperature of the device reaches a certain threshold level. The response time is several seconds because the shape change is caused by heat. The pneumatic actuator was proposed in (9) utilizing pneumatic pressure. This actuator consists of an elastic layer, flow channel and air compressor. The elastic layer is deformed by air pressure. The device becomes too large for tact-cell with an air pump obtaining the air pressure. The magnetic micro actuator⁽¹⁰⁾ was proposed utilizing the repulsive force of the magnet and the electromagnetics. The output is 7.5 mN at the maximum, which is small compared with the 50 mN which is the desired output⁽⁹⁾. Furthermore, the literatures^{(7)–(10)} do not mention the force and position control method. The simultaneous sensorless control of position and force is realized by using a solenoid actuator⁽¹⁴⁾. However, the size of this actuator is $15 \text{ mm} \times 10 \text{ mm} \times 43.5 \text{ mm}$, the maximum generated force is about 35 mN, and the operation stroke is about 1 mm. It is desirable to be smaller size and bigger generated force for tact-cell. Therefore, the authors proposed a compact and lightweight linear actuator⁽¹¹⁾ and showed the possibility of simultaneous control of position and force. Figure 2 shows comparison of mover stroke and maximum force in Refs. (5) (7)–(11). And the characteristics of various actuator in Fig. 2 and input conditions are summarized in Table 1. As

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Fig. 2. Relation between maximum output force and displacement of various actuators

Table 1. The characteristics of various actuator and input conditions in Fig. 2

Actuator	surface area (mm ²)	response speed	input conditions in Fig. 2
Solenoid ⁽⁵⁾	150.0	fast	0.1 A
Piezo ⁽⁷⁾	21.3	very fast	150 V
SMA film ⁽⁸⁾	10.5	slow	0.6 A
Pneumatic ⁽⁹⁾	569.3	slow	100 kPa
Magnetic micro ⁽¹⁰⁾	4.0	fast	0.8 A
Electromagnetic ⁽¹¹⁾	16.0	fast	0.2 A

Fig. 3. Relation between maximum output force per unit area and displacement of various actuators

described above, the surface area of the actuator is also important as the tact-cell, thus the relation between maximum output force per unit surface area and stroke of various actuators are shown in Fig. 3. As a result, the actuator⁽¹¹⁾ is superior to others for a tact-cell. If the output force can be further increased, the performance of this kind of linear actuators is improved as a tact-cell. Therefore, the primary objective of this paper is to increase the output force while maintaining the size. In Ref. (11), the stator was divided into two layers and the thrust force was improved. In this paper, the stator is divided into three layers and laterally stacked in N and S alternately location with a multiple pole. The detailed structure

Fig. 4. Proposed actuator

Table 2. Material used in proposed actuator

Part	Material
Magnet	Neodymium magnet N-50
Mover	Copper
Iron	Carbon steel S50C
Permalloy	permalloy (PC)

is explained in Section 2-1. In general, efficiency of electromagnetic force device is equal to or higher than the actuators in the past literatures^{(5)(7)–(11)}.

The paper is organized as follows. Firstly a novel electromagnetic linear mini-actuator is proposed. The principle of force generation and position estimation are presented in Section 2. The thermal analysis is conducted in Section 3. The experimental results are reported in Section 4. At the end, a conclusion is given and future perspectives are discussed in section 5.

2. Proposed Actuator

2.1 Structure of Proposed Actuator This section explains the structure of proposed actuator. Figure 4 shows a general view and the structure of the proposed actuator. The brown part shows the mover. The blue and silver part shows the stator structure. The actuator consists of iron, magnet, permalloy and coil. The materials used in the proposed actuator are listed in Table 2.

The mover is driven in the vertical direction and the stroke is 1.0 mm. The size per stage is 4.0 mm × 4.0 mm × 3.2 mm. Magnets and iron parts are alternately arranged. Magnetization and current directions are shown in Fig. 4. DC and AC for driving and position estimation are applied.

Figure 5 shows the structure of mover and stator. The mover consists of additional mover and mover for driving. The mover for driving part has 200 turns and the directions of current become alternate clockwise and counterclockwise rotation per each stage. The additional mover for position estimation has 15 turns. Position estimation of the additional mover is explained in Section 2-3. The total number of turns of the mover is 215.

The stators consist of inner stator and outer stators. The stators are mainly made of magnets and iron which are alternately arranged. Permalloy is placed at the core of the additional mover for position estimation. The stators are placed in a multi-layer structure and laterally stacked alternately with mover. This structure increases the magnetic flux linking the

Fig. 5. Structure of mover and stator

Fig. 6. Directions of magnetic flux, Lorentz force and current

mover. Thus, the output force increases compared with previous actuator⁽¹¹⁾. The shape of the outer stator is a square tube to enable the actuators to be arranged in a plane easily.

2.2 Principle of Lorentz Force Generation This section explains the principle of force generation. Figure 6 shows the directions of the magnetic flux, Lorentz force, and current in the mover. The magnetic flux crosses through the movers as shown in Fig. 6. Lorentz force is generated by the product in the current in the movers and the magnetic flux. Therefore, this actuator can realize a pushing motion and a pulling motion by changing the directions of current.

The Lorentz force of the mover F_y is calculated as

$$F = \int_V (\mathbf{J} \times \mathbf{B}) dV, \dots\dots\dots (1)$$

$$F_y = \int_0^{x_1} \int_0^l \int_0^d \frac{2nI}{d(x_1 - x_2)} B_z(x, y, z) dx dy dz, \dots\dots\dots (2)$$

where $\mathbf{J}$, $\mathbf{B}$, V , $B_z(x, y, z)$, and n denote the vector of current density, the vector of magnetic flux density, the area where magnetic flux and movers cross, the magnetic flux density of z-axis direction and the number of turns of the coil. x_1 , x_2 , l , and d define as shown in the Fig. 4.

2.3 Principle of Mover Position Estimation This section proposes a method to use the inductance of the actuator to detect the mover position. The inductance of the actuator is calculated from AC current and AC voltage applied

Fig. 7. Cross-section view of additional mover and stator (Permalloy)

to the movers. This section explains the relation between the inductance and displacement.

Inductance of the actuator L is expressed as

$$L = L_N + L_A, \dots\dots\dots (3)$$

where L_N and L_A denote inductance of the mover for driving, and inductance of the additional mover. The ratio of the inductance L_A to the inductance of the actuator L is large since magnetic flux of the additional mover is larger than that of the mover for driving.

Figure 7 shows a cross-section view of the mover for position estimation. Figure 7(a) is a cross-section view without displacement and Fig. 7(b) is a cross-section view with displacement.

L_A is calculated as

$$L_A = L_\alpha + L_\beta, \dots\dots\dots (4)$$

where L_α and L_β denote inductance of an air core coil and inductance of a permalloy core coil. Permalloy has high permeability and can increase inductance. L_α and L_β are expressed as

$$L_\alpha = K_\alpha \mu_0 N^2 \left(\frac{\pi D^2}{4} \right) l_\alpha, \dots\dots\dots (5)$$

$$L_\beta = K_\beta \mu_0 \mu_r N^2 \left(\frac{\pi D^2}{4} \right) l_\beta, \dots\dots\dots (6)$$

where K_α , K_β , μ_0 , μ_r , N , D , l_α , and l_β denote the Nagaoka coefficient of the air core coil, the Nagaoka coefficient of the permalloy core coil, permeability of vacuum, relative permeability of permalloy, the number of turns per length, the diameter of the mover, the length of the air core coil, and the length of the permalloy core coil.

The permeability of permalloy is very large compared with that of vacuum. Therefore, relation of inductance of an air core coil and inductance of a permalloy core coil is expressed as

$$L_\alpha < L_\beta, \dots\dots\dots (7)$$

The length of the permalloy core coil l_β decreases when displacement of the mover is increased. Therefore, L_A decreases. Relation of inductance of the additional winding is expressed as

$$L_A > L'_A, \dots\dots\dots (8)$$

where L_A and L'_A denote the inductance of Fig. 7(a) and the

Table 3. Simulation parameter in thermal analysis

Parameter	Value
Thermal conductivity of magnet	7.0 W/(m·K)
Specific heat of magnet	410 J/(kg·K)
Density of magnet	7.50 g/cm ³
Thermal conductivity of copper	400 W/(m·K)
Specific heat of copper	380 J/(kg·K)
Density of copper	8.69 g/cm ³
Thermal conductivity of iron	50 W/(m·K)
Specific heat of iron	480 J/(kg·K)
Density of iron	7.80 g/cm ³
Coefficient of heat transfer	5 W/(m ² ·K)
Air temperature	20°C
Internal resistance of movers	1.24 Ω

Fig. 8. Relation between current and temperature of actuator

inductance of Fig. 7(b). Accordingly, the inductance of the actuator L in 3 decreases when displacement of the mover is increased because of the influence of L_A in 4.

Moreover, the inductance of the actuator L is calculated as

$$L = \frac{1}{2\pi f} \sqrt{\left(\frac{V_{amp}}{I_{amp}}\right)^2 - (R + R_s)^2}, \dots \dots \dots (9)$$

where f denote the frequency⁽⁵⁾. Thus, if voltage and current amplitude of the actuator V_{amp} and I_{amp} can be measured, the mover position can be estimated.

3. Thermal Analysis

The recommended temperature of magnets is 80°C or lower since the performance of magnets decline by higher temperature. A large current will heat up the actuator. Therefore, it is necessary to consider the maximum allowable current. Temperatures of magnets and iron parts are calculated by simulation software. These simulations were conducted in a steady state and a transient state by using a magnetic field analysis of the electromagnetic analysis software, “JMag Designer” based on the finite element method. Simulation parameters in thermal analysis are listed in Table 3. They are set as thermal conductivity, specific heat, and density. Air temperature is assumed to be 20°C. Electric power consumption P is calculated as

$$P = I^2 R, \dots \dots \dots (10)$$

where I and R denote current of the movers and internal resistance of the movers.

Figure 8 shows the relation between current and temperature of the actuator. It indicates the thermal equilibrium values when constant DC current is applied to the actuator. The

Fig. 9. Relation between time and temperature of the actuator (0.25 A)

Fig. 10. Fabricated actuator

horizontal axis is current and the vertical axis is temperatures of the inner stator, and outer stator. The temperature of the inner stator is higher than temperature of the outer stator. The temperature of the inner stator was higher than 80°C when the current was over 0.25 A. Additionally, Fig. 9 shows the relation between time and temperature of the actuator (0.25 A). It indicates that the time until the temperature of inner stator reach about 80°C takes between 100 and 120 minutes. Hence, DC current 0.25 A can be applied to the actuator.

4. Experiments

This section describes the experimental results. The experiments of output force measurement and inductance measurement were conducted to verify the validity of proposed actuator.

4.1 Fabrication of Actuator Figure 10 shows the fabricated actuator. A copper which a wire diameter is 0.18 mm was used for the mover. Since the shape of mover can not maintained with copper wire alone, the mover is fixed with an epoxy resin type adhesive. The stator parts are fixed to the plastic parts made with 3D printer.

4.2 Experimental System This section explains the experimental system.

The experimental system is shown in Fig. 11. The experimental parameter is in Table 4. A high speed digital control system called ‘PE-Expert4’ made by Myway plus Corporation was used. The main CPU is a digital signal processor (DSP). The A/D converter samples the data every 8 μs. The D/A converter outputs a signal every 8 μs. The AC 500 mV voltage is used for position estimation which is generated by

Table 4. Experimental parameter

Cut-off frequency of HPF	1.59 kHz
Initial position (Mover)	0.3 mm
Shunt resistance	1.0 Ω
Gain of amplifier	8.18
Amplitude of the AC voltage	500 mV
Frequency of the AC signal	100 kHz
Amplitude of the DC voltage	650 mV
Sampling time of A/D converter	8 μ s
Sampling time of D/A converter	8 μ s

The controller generates the digital signals. The digital signals pass through the D/A converter, and adder circuit. The signals are changed to a voltage including AC and DC components by adder circuit and applied to the actuator. DC components is not needed for estimation of the accurate position. Hence, DC components are removed by high-pass filter after passing through the actuator. The cut-off frequency was set to 1.59 kHz. The gain of amplifier was set to 8.18.

The experimental circuit is shown in Fig. 12.

4.3 Output Force Measurement This section explains the experiment of output force measurement. Figure 13 shows the experimental equipment. The XYZ stage and load cell which is fixed to XYZ stage severally measures displacement and output force of the actuator. The digital indicator is used to display output force. Specifications of the load cell, and the digital indicator are listed in Table 5.

Table 5. Specifications of equipment

Equipment	Load cell	Digital indicator
Model	ULA-10GR	CSD-815B
Maker	Minebea Co., Ltd.	Minebea Co., Ltd.
Repeatability	0.1961 mN	—
Rating	98.07 mN	—

Figure 14 shows the experimental results and the simulation results of the Lorentz force. The horizontal axis is displacement of the mover and the vertical axis is the Lorentz force of the actuator. Displacement of the mover is from 0.0 mm to 1.0 mm. The maximum Lorentz force is 66.9 mN. The experimental result almost coincides with the JMAG simulation result⁽¹⁵⁾.

Figure 15 shows relation between maximum output force per unit area and displacement of proposed actuator and various actuators. The proposed actuator has better performance in term of output force per unit area and displacement between 0 mm and 1.0 mm compared with other actuators. Therefore, the proposed actuator is superior as an actuator for tact-cell.

4.4 Inductance Measurement This section explains the experiment of inductance measurement. The ‘PE-Expert4’ measures voltage and current amplitude of the actuator V_{amp} and I_{amp} . The laser sensor measures displacement of the mover.

Figure 16 shows the relation between the I_{amp} , V_{amp} and displacement. The horizontal axis is displacement of the mover and the vertical axis is the voltage and current amplitude of the actuator.

The inductance is estimated using by the data of Fig. 16

Fig. 15. Relation between maximum output force and displacement of proposed actuator and various actuators

Fig. 16. Relation between I_{amp} , V_{amp} and displacement. (Experiment)

Fig. 17. Relation between estimated inductance and displacement. (Experiment)

and (9). Figure 17 shows the relation between the estimated inductance and displacement. Inductance of the actuator L is decreased when displacement is increased. Therefore, the mover position can be estimated by the voltage amplitude and the current amplitude of the actuator.

5. Conclusion

This paper focused on a novel compact actuator aiming at realization of a two-dimensional tactile display. The proposed electromagnetic linear actuator can accurately control the position and force, while being compact and lightweight as a tact-cell. The 3D size of the actuator is $4.0 \text{ mm} \times 4.0 \text{ mm} \times 34.0 \text{ mm}$. The verification experiments were conducted with the system that DC and AC voltage are applied to actuator simultaneously. The result of output force measurement shows that the proposed actuator has better performance in term of output force per unit surface area and mover stroke between 0 mm and 1.0 mm compared with other actuators. Further the result of inductance measurement shows that the proposed actuator can be sensorlessly controlled by using the voltage and current amplitude of the actuator.

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