A Stacked-type Electrostatic Actuator and Measurement of its Energy Efficiency

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Abstract We have studied a stacked-type electrostatic actuator by folding two ribbon electrodes in an alternate configuration. The energy efficiency of this type of actuator was investigated using the thick-electrode-part actuator and triangle-shaped actuator. The maximum energy efficiency levels were 30–40% for the thick-electrode-part actuator and 40–50% for the triangle-shaped actuator.

Keywords electrostatic actuator, stacked-type, energy efficiency

1. Introduction

We have been studying the lightweight stacked-type electrostatic actuator, with the view of using it as an artificial muscle in robots [1]. Generally, the generated force of an electrostatic actuator is weak in comparison to other actuators in the macro-scale. However, an electrostatic actuator can generate large forces that are comparable to those produced by conventional actuators, such as electromagnetic motors, when the gap between the electrode parts is sufficiently narrow. Furthermore, an electrostatic actuator is superior in terms of power/weight ratio and energy consumption, since it is made of lightweight materials and in principle no current is needed while it is held in position. Moreover, it can achieve practical force and stroke by integration and piling up [2-4].

Previously, we had investigated the contractile characteristics of this actuator and improved the structure that render it more stable in terms of overload, and examined a scaled-down actuator that generates larger forces [5, 6]. In the present study, we measured the energy efficiencies of two types of stacked-type electrostatic actuator and studied their characteristics.

2. Basic Structure

2.1 Structure

The basic structure of the stacked-type electrostatic actuator is shown in Fig. 1. This actuator was constructed by alternately folding two ribbon electrodes around each other in the manner of a paper spring. The ribbon electrode consists of a thin metallic conductor sandwiched between two thin plastic films. By applying a high voltage to one ribbon electrode and grounding the other ribbon electrode, each electrode layer becomes charged and an attractive force is generated. This attractive force is equivalent to the magnitude of the electrostatic force generated in a capacitor that consists of two dielectric layers, as illustrated in Fig. 2. The attractive force is given by the following equation:

\[ F = \frac{\varepsilon_0 SV^2}{2\varepsilon_2 \left( \frac{1}{\varepsilon_1} + \frac{d}{\varepsilon_2} \right)^2} \]  

where \( V \) is the applied voltage, \( \varepsilon_0 \) is the dielectric constant in a vacuum, \( t \) and \( \varepsilon_1 \) are the thickness and dielectric constant of the plastic films, respectively, \( d \) and \( \varepsilon_2 \) are the thickness and dielectric constant, respectively, of the dielectric area of a gas or liquid, and \( S \) is the electrode area. This equation indicates that the generated force is in inverse proportion to the square of the value of the gap length between the facing electrodes. Therefore, this actuator is miniaturized in order to increase the force per unit area. Through perpendicular stacking and assembly in parallel, as shown in Fig. 3, this actuator can achieve large displacement and large force, even in the macro-scale.

Fig. 1. Basic structure of the stacked-type actuator

Fig.2. Equivalent capacitance
2.2 Generated force

The generated force in air measured by the present actuator is shown in Fig. 4.

![Generated Force](image)

3. Energy efficiency

3.1 Method of measurement

It is necessary to measure energy output and electric energy input to assess energy efficiency. Therefore, a voltage was applied to the actuator attached to a weight in air, so that the dynamic energy was measured by pulling up the weight. For a given electric energy, the flowing current while operating was measured using the electro meter (Keithley model 6514), and subsequently given electric energy was derived from the current value. In addition, since the amount of the contraction of the actuator was small in this measurement, the amount of contraction was amplified using the optical balance. The optical balance under the above measurement conditions is illustrated in Fig. 5. The actuator was placed at one end of the bar. Small mirrors were placed at the center of the bar and above the balance. Thus, any motion of the actuator would be amplified by reflection of the laser beam onto the floor by the two mirrors. A movement of 1.0 mm in the laser spot corresponded to expansion or contraction of the actuator by 21.5 μm.

3.2 Actuator modifications

The square-shaped actuator constructed previously suffered from the problem that it would overextend when overloaded, and the electrostatic force would cease to work. The structure of the stacked-type actuator needed to be improved so that it would perform in a stable fashion even when overloaded. Previously, the original actuator had been improved in two new models. The first type of improved actuator involves thickening the electrode parts relative to the hinge part [7], to produce an actuator with the thick-electrode-part, illustrated in Fig. 6 (a). This structure is not easily overextended, as deformation of the electrode parts is moderated when the load is applied. The second type of improved actuator is the triangle-shaped actuator, illustrated in Fig. 6 (b) [8]. A square-shaped actuator differs from a triangle-shaped actuator in terms of the number of sides that remain free after folding. In the square-shaped actuator, two of the four sides are free, whereas in the triangle-shaped actuator, only one of the three sides is free; therefore, the triangle-shaped actuator has a more stable structure. We have recently carried out scale-down procedures to produce an actuator to 0.7 mm width. However, in the present study, comparatively large actuators were used in order to obtain sufficient output with a single actuator. The electrode areas of the thick-electrode-part actuator and that of triangle-shaped actuator are approximately 25 mm² and 20 mm², respectively. The construction methods for these two actuators are described below.

![Improved stacked-type actuators](image)

A. Thick-electrode-part actuator

Copper leaf (thickness of 0.2 μm) was used as the conductor of the ribbon electrode and the plastic film was composed of PET (polyethylene terephthalate). For the hinge part of the ribbon electrode, a thin film was constructed by sandwiching copper leaf between two PET films (thickness of 1.5 μm). PET films (thickness of 50 μm) with an adhesive layer on one side were then placed on either side of the thin film of this hinge layer at intervals.
of 0.3 mm. The PET films were adhered by subjecting them to thermocompression at 100°C, and then cutting the material into 5.4-mm-wide ribbons. The ends of the two ribbons were adhered to each other, and two ribbons were folded alternately around each other at an angle of 90°. The photographs of the constructed ribbon electrode and the actuator are shown in Fig. 7. This actuator comprised 40 electrode layers.

![Figure 7](image1.png)

**Fig.7**. Photograph of the thick-electrode-part actuator (a) Ribbon electrode (b) thick-electrode-part actuator

B. Triangle-shaped actuator

The triangle-shaped actuator was constructed by producing two ribbon electrodes and then folding them alternately around each other, in almost the same manner as for the square-shaped actuator. Gold leaf (thickness 2.5 \(\mu\)m, width 6 mm, length 150 mm) was used as the conductor of the ribbon electrode, and PET films (thickness of 15 \(\mu\)m) with an adhesive layer on one side were used as the plastic films. The ribbon electrode was constructed by sandwiching the gold leaf between two PET films, subjecting the three layers to thermocompression at 180°C, and then cutting the material into 8-mm-wide ribbons. The two ribbons were then folded alternately around each other at an angle of 120°. By folding two 8-mm-wide ribbons into a 10-mm high triangular tower, as shown in Fig. 8(a), we were able to reduce the elastic force during operation. Aluminum plates (0.5-mm thickness) were attached as terminals to the top and bottom electrode layers using a conductive adhesive. In order to harden the conductive adhesive, the actuator was clamped in the completely contracted state (about 3 mm in length) and heat-treated at 120°C. The natural length of the actuator was approximately 5 mm due to the residual stress on the hinge parts. A photograph of the completed triangle-shaped actuator is shown in Fig. 8(b). This actuator comprised 40 electrode layers.

![Figure 8](image2.png)

**Fig.8**. Triangle-shaped actuator (a) Folding method (b) triangle-shaped actuator

### 3.3 Derivation of energy efficiency

The electric energy is given by the time integration of the product of the current during operating and the applied voltage. The dynamic energy output is given by the path integration of the sum of the weight and elastic force, since the actuators have elastic force. Therefore, the dynamic energy output can be derived from the following equation:

$$\int_0^{t_f} (mg + f(x))dx$$

(2)

where \(m\) is the mass of the load used, \(L\) is the length of the expansion from the natural length of the actuator before application of the voltage, \(l\) is the length of the contraction from the natural length of the actuator during application of the voltage, and \(f(x)\) is the elastic force. As mentioned above, the energy efficiency of the actuator is given by the following equation:

$$\eta = \frac{\int_0^{t_f} (I(t)Vdt) + \int_{-L}^{l} f(x)dx}{\int_0^{t_f} I(t)Vdt}$$

(3)

where \(t\) is the driving time. In addition, for the triangle-shaped actuator, \(f(x)\) was given by \(1.8x\) approximately. For the thick-electrode-part actuator, the elastic characteristic was that of a nonlinear spring, as shown in Fig. 9. Therefore, \(f(x)\) can be approximated using the following functions:

$$f(x) = \begin{cases} 
4.7x^2 & (x < 0) \\
1.3x & (0 < x < 1.35) \\
2.3x & (x > 1.35)
\end{cases}$$

(4)

![Figure 9](image3.png)

**Fig.9**. Elastic characteristics of the thick-electrode-part actuator

### 3.4 Results of the measurements

The energy efficiency was derived from the measurement value of the current and Eq. (3). The given weights were 0.5 g, 0.6 g, and 0.7 g. The phenomenon of...
A Thick-electrode-part actuator

An example of the current flowing during operation of the actuator is shown in Fig. 10. A sharp peak was observed, regardless of the voltage or weight applied. Furthermore, a slight current was retained, although in principle no current is needed while the actuator is held in position. This phenomenon was probably the result of incomplete insulation.

The energy efficiency results are shown in Fig. 11. The maximum energy efficiency was 30–40% for each weight, when the minimum pull-in voltage was applied. The energy efficiency decreased as the applied voltage increased from the minimum pull-in voltage.

B Triangle-shaped actuator

An example of the current flowing during operation of the actuator is shown in Fig. 12. The shape of the curve was the same as that seen for the thick-electrode-part actuator. The current during position holding was found to be negligible compared to the current during operation. The energy efficiency results are shown in Fig. 13. The maximum energy efficiency was 40–50% for each weight when the minimum pull-in voltage was applied.

4. Discussion

4.1 Problems associated with the thick electrode actuator

The energy efficiency of the thick-electrode-part actuator was lower than that of the triangle-shaped actuator. The distance between the conductors while holding position was about 100 μm for the thick-electrode-part actuator and about 30 μm for the triangle-shaped actuator. Therefore, the accumulated electrostatic energy of the thick-electrode-part actuator, which is not used as the output, is lower than that of the triangle-shaped actuator. Therefore, the energy efficiency of the thick-electrode-part actuator is expected in principle to be better than that of the triangle-shaped actuator. This phenomenon probably results from the elastic characteristic of the thick-electrode-part actuator. The ideal spring constant for our actuator is infinite like stopper at the overload region and is very small at the working region. However, since the thickness of the electrode and the length of the hinge were not adequate for the area of the electrode in terms of this thick-electrode-part actuator, the spring constant was 1.3 N/m at the soft region and 2.3 N/m at the hard region; there was no obvious difference between these two regions. Due to this spring characteristic, stability was lost, actuator torsion occurred, and the minimum pull-in voltage increased, and so the energy efficiency was lowered. In the future, we will perform these measurements using a thick-electrode-part actuator of better design.
our actuator will be improved by thickening the electrode part of the triangle-shaped actuator in order to derive a more stable structure.

4.2 Problems common to both actuator types

The thick-electrode-part actuator and triangle-shaped actuator have some problems in common. One problem is energy loss due to collisions between electrode parts. Since the electrostatic force is in inverse proportion to the square of the value of the applied voltage, the collision energy increases or the energy loss increases as the applied voltage increases. Another problem is that the electrostatic energy that cannot be taken as output becomes charged by necessity. In order to solve these problems, voltage control and reuse of the electrostatic energy are required.

5. Conclusion

Measurements of the energy efficiencies of stacked-type electrostatic actuators were performed using the thick-electrode-part actuator and the triangle-shaped actuator. As a result, the efficiency of the thick-electrode-part actuator was 30–40%, and that of the triangle-shaped actuator was 40–50%. The energy loss resulted from the incomplete elasticity and inadequate design of the ribbon electrode. We plan to measure the energy efficiency of a stacked-type electrostatic actuator that has superior elastic properties. Furthermore, energy efficiency will be improved by establishing the method of reusing the accumulated electric charge and voltage control.

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References