Development of fish robot using stacked-type electrostatic actuators

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Abstract—We have been studying a stacked-type electrostatic actuator, in view of using it as artificial muscle in robots. This actuator is constructed by alternately folding around each other two ribbons of metallic conductor sandwiched between thin plastic films, and it can drive perpendicularly to the surface of the electrodes. Previously, we had constructed a regular square-shaped stacked-type electrostatic actuator. In this study, we improved the actuator by changing the shape of the electrode parts to a triangle, so that the actuator can work stably even when overloaded. Then, we constructed a fish robot using a driving mechanism which alters the perpendicular motion to a rotational motion, by arranging these triangle-shaped actuators as antagonist muscles. As a result, we succeeded in constructing a fish robot which swam at a speed of about 2 cm/sec.

Index Terms—electrostatic actuator, fish robot, spring constant, stacked-type

I. INTRODUCTION

Recently, many kinds of electrostatic actuators have been studied. An electrostatic actuator can achieve large forces, comparable with those of conventional actuators such as electromagnetic motors, when the gap length between the electrode parts is sufficiently narrow. Furthermore, an electrostatic actuator is superior in terms of the power/weight ratio and energy consumption, because it is made of lightweight materials and in principle no current is needed while its position is static. Therefore, electrostatic actuators have been studied in view of their use as artificial muscles in robots. There are two types of stacked-type actuator. One type drives perpendicularly to the surface of the electrodes, and relatively large displacements can be achieved by piling up many electrode layers [1], [2], [3]. The other type drives in parallel to the surface of the electrodes, and relatively large displacements can be achieved by arranging many electrodes into a stripe [4]. Generally, since perpendicular-type actuators have no friction and do not need high-frequency alternating current to work, they consume less energy than parallel-type actuators. However, although several perpendicular-type actuators have been reported until now, they have had problems pertaining to elasticity: they cannot achieve sufficient displacement because of the stiff structure, or the gap between the electrodes is excessively widened because the structure is too soft, and so the electrostatic force cannot work effectively. We have been studying the stacked-type electrostatic actuator, which is constructed by alternately folding two ribbon electrodes around each other; this type of actuator drives perpendicularly to the surface of the electrodes. The above-described elasticity problem has been solved for this type of actuator by thickening the electrode parts of the actuator [5]. In this study, a stacked-type actuator with triangle-shaped electrode parts was constructed in order to render it more stable, and the elastic force and the generated force of the actuator were measured. Then, a driving mechanism using these triangle-shaped actuators was constructed and incorporated into a new fish robot, as an example of use of these actuators as artificial muscles, and an experiment in dielectric fluid was performed.

II. BASIC STRUCTURE OF THE PROPOSED ACTUATOR

The basic structure of the stacked-type electrostatic actuator is shown in Fig. 1. This actuator is constructed by alternately folding two ribbon electrodes around each other. A ribbon electrode consists of a thin metallic conductor sandwiched between two thin plastic films. By applying high voltage to one ribbon electrode and grounding the other, 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 capacitance consisting of two dielectric layers, and the attractive force is given by the following equation:

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

where \( V \) is the applied voltage, \( \varepsilon_0 \) is the dielectric constant in 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 actuator does not lose any driving force because the electrostatic force works perpendicularly to the electrodes; it can achieve large displacements because many electrode parts are piled up perpendicularly. Therefore, this actuator can used as an artificial muscle in a robot.

III. TRIANGLE-SHAPED ACTUATOR

A. Characteristics

The square-shaped actuator constructed first had a problem...
in that it would extend too much when overloaded, and the electrostatic force would cease to work. In order to improve this stacked-type actuator and render it more stable, a triangle-shaped actuator was developed. A square-shaped actuator differs from a triangle-shaped actuator in the number of edges which remain free after folding. In the square-shaped actuator, two of four sides are free, but in the triangle-shaped actuator only one of three sides is free; therefore, the triangle-shaped actuator has a more stable structure. Even as we constructed these two types of structure out of paper ribbons, it was clear that the triangle-shaped structure could not be extended easily, confirming that it is more stable than the square-shaped structure (Fig. 2).

B. Construction

A triangle-type actuator was constructed by making two ribbon electrodes and then folding them alternately around each other, in almost the same way as for the square-shaped actuator. Gold leaf (thickness 2.5 μm, width 6 mm, length 150 mm) was used as the conductor of the ribbon electrode, and PET (polyethylene terephthalate) films (thickness of 15 μm) with an adhesive layer on one side were used as the plastic films. The ribbon electrode was constructed by sandwiching 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. Then, two ribbons were 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. 3(a), we were able to reduce the elastic force during operation. In this case, the effective electrode area was about 20 mm². Aluminum plates 0.5 mm thick were attached as terminals to the top and bottom electrodes layers using conductive adhesive. Here, in order to harden the conductive adhesive, the actuator was clamped in the completely contracted state (about 3 mm long) and heat-treated at 120°C. Consequently, the natural length of the actuator became about 5 mm due to the residual stress of the hinge parts. The natural length of the actuator can be changed by expanding or contracting the actuator and heat-treating it in that state at 140°C. A photograph of the completed triangle-shaped actuator is shown in Fig. 3(b).

C. Spring constant

The spring constant of the constructed triangle-shaped actuator was measured. The test apparatus was a optical balance, so that any motion of the actuator would be amplified [6]. The expansion and contraction of triangle-shaped actuators with a natural length of 5 mm, 8 mm or 10 mm are shown in Fig. 4. The graphs for the 8-mm and 10-mm actuators indicate that the spring constant is small for the contracted region, but large for the expanded region, especially for the excessively expanded region. This type of spring constant is effective when load is applied to the actuator perpendicularly. Namely, the actuator contracts softly at the working region and hard at the overload region, and therefore the electrostatic force is allowed to work effectively. The ideal spring constant is infinite at the overload region and zero at the working region. Although the spring constant of the triangle-shaped actuator was large at the working region and insufficiently large at the overload region compared to the ideal one, the triangle-shaped actuator still surpassed the square-shaped actuator by being more stable. On the other hand, in the 5-mm actuator, the contracted region and the expanded region had the same spring constant. The 5-mm actuator was adopted for the fish robot for the reasons explained in the following paragraph.

D. The adopted actuator

Fig. 4 suggests that the total length of the actuator, whose
spring constant begins to increase when the actuator contracts, changes with the natural length of the actuator. The amount of contraction and displacement at which the spring constant begins to increase and the geometric minimum lengths for the natural lengths of 5 mm, 8 mm and 10 mm are shown in Table 1. This table indicates that the 5-mm actuator can almost completely contract, whereas the 8-mm and 10-mm actuators cannot contract completely. This is probably due to the fact that the hinge parts memorize the form of the expanded actuators when they are heat-treated. In the 5-mm actuator, it is thought that the hinge parts are squashed to some extent like hairpins when the actuator is in its natural state, as shown in Fig. 5(a), and so the actuator can contract almost completely, as shown in Fig. 5(b). On the other hand, in the 8-mm and 10-mm actuators, the shape of the hinge parts is probably as shown in Fig. 5(c) when the actuators are in their natural state. When the 8-mm and 10-mm actuators contract, they contract softly and the shape of the hinge parts becomes as shown in Fig. 5(d), because the length of the electrode parts is sufficiently larger than that of the hinge parts. However, when the shape becomes as shown in Fig. 5(e), the spring constant becomes large because an additional force is needed to flatten the hinge parts with their memorized form. Furthermore, since the curvature radius of the hinge parts increases as the natural length increases, and the hinge parts memorize this curvature radius, the spring constant becomes quite large in long actuators. Thus, if the spring constant in the contracted state is large, the generated electrostatic force cannot contract the actuator completely, to the geometric minimum length. Since the electrostatic force increases as the gap length between the electrodes decreases, the 5-mm actuator, which contracts nearly completely, was adopted in this study. Although the 5-mm actuator does not have a low spring constant region unlike the other two actuators, this actuator can still be used since the spring constant is not so large.

### E. Generated force

The force generated by the 5-mm actuator was measured using the optical balance [6]. The result of measurement in air is shown in Fig. 6. The theoretical value was calculated from (1), on the assumption that the electrode layers are parallel to the plate, using the gap length between the electrodes as calculated from the thickness of the ribbon electrodes, the thickness of the aluminum terminals and the number of electrode layers. This result confirmed the fact that the generated force is comparable to the theoretical value.

### IV. DRIVING MECHANISM

#### A. Design

A driving mechanism was developed, which converts perpendicular motion into rotational motion in a joint. A schematic diagram of the driving mechanism is shown in Fig. 7. The driving mechanism is basically comprised of two actuators arranged as antagonist muscles. Thus, the movable part connected to the actuators inclines when voltage is applied only
to one actuator. The movable part and central plate consist of a 0.5-mm thick PET plate, and the movable part is connected to the central plate by a hinge made of 4.5-μm thick PET film. The movable part is 20 mm×10 mm, and the height is determined by the length of the actuator attachments. Furthermore, a hinge made of 4.5-μm thick and 1-mm long PET film was used to connect the movable part to the actuator, so that the electrodes of the actuators would not be deformed by the inclination of the movable part. In addition, since the 5-mm actuators used for the driving mechanism did not achieve a large stroke, the actuators with a natural length of 5 mm were expanded to 6 mm and they were attached into the driving mechanism.

**B. Drive experiment**

A drive experiment with the constructed driving mechanism was performed, and the angular velocity was measured. The measurement method is shown in Fig. 8. A mirror was attached to the movable part of the driving mechanism, so that it could reflect a laser beam. Four phototransistors were placed in line where the reflected laser beam would arrive with the motion of the movable part. The locations where photo-transistors were placed were equivalent to 15.5°, 6.6°, -5.4°, and -12.3° of rotation of the movable part. Then, the duration of movement of the laser beam in each interval was measured using an oscilloscope. This experiment was also performed in insulated liquid (Fluorinert). The duration of movement and the angular velocity at intervals a, b, and c, shown in Fig. 8, at DC voltages of 1400 V and 1800 V are respectively shown in Tables 2(a) and 2(b). The results indicate that the movable part accelerated as the angle approached 0°. This is because the restoring force (the elastic force of the opposite actuator) was added to the electrostatic force. It was also found that the movable part slowed down as the angle deviated from 0°. Generally, the angular acceleration becomes positive because the electrostatic force increases in inverse proportion to the square of the gap distance between the electrodes, while the reaction force (elastic force) increases with the contraction of the actuator. This is probably why Fluorinert induced squeeze-film damping between the electrode parts. Squeeze-film damping is the restoring force generated when two films with a narrow gap are either pressed closer together or pulled apart. Since this force is proportional to the velocity and is inversely proportional to the third power of the gap distance between the electrode parts, squeeze-film damping probably plays the role of a brake, slowing down the motion.

**V. FISH ROBOT**

**A. Mechanism**

Various swimming styles have been used for the propulsion of fish robots, but those which require complicated wiring and many actuators were not suitable to our design because our actuator works only with high voltages. The simplest swimming style in which the fin rotates around the supporting point was adopted, but the propulsion efficiency was not good. The dominant fluid force of this propulsion method is the mass force which is added when a rigid body accelerates or slows down in fluid. This additional mass is the mass which is added when a rigid plate accelerates or slows down, and the magnitude of the additional mass depends on the shape of the plate. The additional mass force is the product of the additional mass and the acceleration of the plate in the fluid, and the direction of the additional mass force is contrary to the direction of the acceleration of the plate; therefore the additional mass force is inertia force. The additional mass force generated while a plate of the length 2a is moving with the acceleration \( \alpha \) is given by the following equation:

\[
F = -m' \alpha, \quad m' = \rho \pi a^2, \quad (2)
\]

where \( m' \) is the additional mass and \( \rho \) is the density of the fluid. With this swimming style, an additional mass force is generated perpendicularly to the rigid plate when the rigid body performs an angular acceleration movement around the circumference of the supporting point as shown in Fig. 9. The forward thrust
component of this force serves as the propulsive force in this swimming style. Here, if the mass point is at distance \( r \) from the supporting point, the propulsive force \( f \) is given by:

\[
f = m' r \dot{\theta} \sin \theta, \quad m' = \rho \pi a^2,
\]

where \( \theta \) is the rotation angle of the rigid body plate. Furthermore, as shown in Fig. 9, when this rotational movement around the circumference of the supporting point of the rigid plate is divided into four phases, the forward thrust component of the additional mass force always serves as forward propulsion at each phase, by providing the ideal angle acceleration. This ideal angular acceleration means that the angle acceleration is positive relative to the direction of movement of the rigid plate when the rigid plate approaches the rotational center (\( \theta \) approaches 0°), and the angular acceleration is negative relative to the direction of movement of the rigid plate when the rigid plate deviates from the rotational center. Since the angular acceleration of the constructed driving mechanism is nearly ideal, it is likely that the force always provides forward propulsion.

B. Construction

A fish robot was constructed using the constructed driving mechanism. The main material was plastic plate. The total length of the fish robot was about 7 cm, the width was 2 cm and the weight was about 4.5 g. For the fins, 3-cm long, 1.5-cm wide and 25-\( \mu \)m thick films were used. Leads only 25-\( \mu \)m in thickness were used for applying the voltage to the actuators, so that the influence of the hardness of leads would be reduced as much as possible. A photograph of the constructed fish robot is shown in Fig. 10.

The driving circuit was designed to apply high voltages to the left and right actuator alternately, at a frequency of 1Hz or 5Hz. In addition, 10-M\( \Omega \) resistances were connected in parallel with the actuators, so that the charge in a given actuator could be immediately released when voltage was not applied to that actuator. Furthermore, by designing this circuit so that it was possible to make only one actuator work for an extended period, we were able to make the fish robot turn.

C. Drive experiment

A drive experiment was performed in Fluorinert at a DC voltage of 1400 V. As a result, the fish robot swam straight at a speed of about 2 cm/sec when the alternation frequency between the left and the right actuator was 5Hz. The straight swimming is shown in Fig. 11(a), and the turning is shown in Fig. 11(b). There was a difference between the angle of the left turn and the angle of the right turn.

D. Propulsive force

The propulsive force in the case of straight swimming was measured. The measurement method is shown in Fig. 12. The fish robot was hung from a high position using leads, and it was made to perform swimming motions. Then, the propulsive force was calculated from the distance at which the moments became balanced. Here, 0.2-mm thick leads were used so that they would not interfere with the experiment. The moment under such conditions is based on the propulsive force, gravity, buoyancy, and the gravity of the leads. The following formula gives the balance of these moments:

\[
\frac{l}{2} M g \cdot \sin \theta + l m g \cdot \sin \theta = l F \cdot \cos \theta + l \rho V g \cdot \sin \theta,
\]

where \( l \) is the length of the leads, \( M \) is the mass of the leads, \( \theta \) is the angle of the leads relative to the vertical direction, \( m \) is the mass of the fish robot, \( F \) is the propulsive force, \( \rho \) is the density of Fluorinert, and \( V \) is the volume of the fish robot. Here, \( \sin \theta = x/l \) and \( \cos \theta = 1 \) are sufficiently small, and so the propulsive force is given by:

\[
F = \frac{gx}{l} \left( \frac{M}{2} + m - \rho V \right),
\]

When the variables were assigned their values, including the measured distance (\( x \)), the propulsive force, \( F \), was found to be about 3.5x10\(^{-4}\) N at the alternating frequency of 5 Hz.
VI. DISCUSSION

A. Difference between the left and the right turn of the fish robot

It is likely that the difference between the left and the right turn resulted from uneven spring constant, generated force and response of the actuators, because the actuators were hand-made. Since a square-wave voltage was applied only to the actuator performing the turn, the force which returned the movable part of the driving mechanism to the position of balance was only the elastic force. Therefore, because the velocity of the left and right actuators differed, the angle of the left turn and the right turn of the fish robot differed. An automatic actuator-folding machine is required to make the actuators identical.

B. Reduction of contraction

The more times voltage was applied to an actuator, the less it contracted. It is likely that this phenomenon results from the lack of an overload region, which has a sufficiently large spring constant. When the actuator was made to contract repeatedly for several minutes, some stiction of the electrode layers occurred because of the charge-up of the insulator. Since some gaps between electrodes became narrow, others became large. If an actuator has no overload region or the spring constant of the overload region is not sufficiently large, many gaps remain expanded, and so the electrostatic force between the gaps becomes small, preventing the actuator from contracting as a whole. This phenomenon may occur even if electric charge does not accumulate. The gaps between the electrodes of an actuator are not completely uniform in length, and the contraction process starts with the smallest gap (Fig. 13(a)). As a result, contracting parts alternate with expanding parts during contraction, and the attractive force between the electrodes becomes weak (Fig. 13(b)). However, an actuator with a sufficiently large spring constant at the overload region does not produce the critical proportion of expanded gaps, and so it is likely that such an actuator will contract completely, without loss of electrostatic force. In our fish robot, the actuators expanded and contracted only within a limited range. Since the actuators did not expand excessively, emphasis was put on complete contraction, to the geometric minimum length, rather than on the presence of a workable overload region. However, it is likely that an actuator with a sufficiently large spring constant at the overload region is required even in this case. Since it is still not clear why the contraction was imperfect, further studies will be required in the future to elucidate this matter.

VII. CONCLUSION

A stable stacked-type actuator was constructed by alternately folding ribbon electrodes around each other so that the electrode parts become triangle-shaped. Then, a driving mechanism which changes perpendicular motion into rotational motion in a joint was constructed by arranging these two actuators as antagonist muscles. A fish robot was constructed with this driving mechanism, and it was able to swim in a dielectric fluid at a velocity of about 2 cm/sec and a propulsive force of about 3.5×10^-4 N when the applied voltage was 1400 V. There were two main problems: one was the uneven performance of the two actuators, and the other was the gradual decrease in the amount of contraction as the movement continued, due to the lack of an overload region where the spring constant is large. In order to solve the first of these problems, an automatic actuator-folding machine must be constructed. The second problem is addressed by improving the spring constant of the actuator; this can be achieved by thickening the electrode parts of the triangle-shaped actuator and thinning the hinge parts. Furthermore, the actuator must be miniaturized in order to increase the electrostatic force and reduce the applied voltage.

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REFERENCES