Development of Flexible Thin Actuator Driven by Low Boiling Point Liquid

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Abstract—In this paper, an flexible thin actuator driven by low boiling point liquid that can generate large force in expansion was proposed and tested. The tested actuator is an envelope-type actuator that is made of laminating plastic sheets, low boiling point liquid and a flexible heater. The flexible heater is made of functional liquid using carbon nanotubes. In a preliminary experiment, by folding serial envelope-type actuators alternately, the actuator can generate the larger displacement towards a specific direction by using air pressure of about 100 kPa. The actuator was also able to drive the load of 490 N. In addition, the performance of the flexible thin actuator driven by the low boiling point liquid and the flexible heater was also investigated. As a result, it was confirmed that the tested actuator could be driven silently by using the fluidic power generated by the electric power.

Index Terms—flexible thin actuator, low boiling point liquid, flexible heater, mobile rehabilitation device, silent movement

I. INTRODUCTION

Due to the aging of Japanese society and the decreasing birth rate, an important problem to keep a quality of life (QOL) for the elderly has occurred [1]. Especially, the decrease in physical ability of the elderly will be concerned to increase in nursing care task. Therefore, the national budget for social welfare will be increased. In order to solve this problem, that is to improve a quality of life (QOL) for the elderly and the disabled and decrease the budget for nursing care, a simple rehabilitation device will be one of solutions. The actuator used in such a rehabilitation device requires lightweight, softness, small size and larger generated force that can support human body [2]-[4]. Therefore, many researchers are studying wearable actuators such as a McKibben artificial muscle [5]-[7]. The McKibben actuator can generate larger force that is more than 300 N by using the actuator whose diameter of 10 mm in the initial condition. However, the actuator can not work with long stroke. Maximum stroke is one fourth of the original length of the actuator. If a thinner actuator that can work with long displacement can be realized, it is useful to apply the rehabilitation or training devices. In our pervious study, we proposed and developed the thinner and lighter wearable actuator that can work toward a particular direction. Fig. 1 shows the construction of an envelope-type actuator. The actuator consists of four sheets of paper and plastic laminate films as shown in Fig. 1. The left figure in Fig. 1 shows the shape of paper A and B. The right figure shows the sectional structure of the actuator. The paper B works as a gusset in the actuator. The size of plastic laminate film is larger than the size of paper A and B. The plastic laminate films are bonded each other at the margin of the films with the exception of paper area. Then, the length of $L_A$, $L_B$ and $H$ in paper A and B is 90 mm, 110 mm and 40 mm, respectively.

II. FLEXIBLE THIN ACTUATOR

A. Construction and Operating Principle

If a thinner actuator that can work with long displacement can be realized, it is useful to apply the rehabilitation or training devices. In our previous study, we proposed and developed the thinner and lighter wearable actuator that can work toward a particular direction. Fig. 1 shows the construction of an envelope-type actuator. The actuator consists of four sheets of paper and plastic laminate films as shown in Fig. 1. The left figure in Fig. 1 shows the shape of paper A and B. The right figure shows the sectional structure of the actuator. The paper B works as a gusset in the actuator. The size of plastic laminate film is larger than the size of paper A and B. The plastic laminate films are bonded each other at the margin of the films with the exception of paper area. Then, the length of $L_A$, $L_B$ and $H$ in paper A and B is 90 mm, 110 mm and 40 mm, respectively.
Fig. 2 shows the view of movement of the envelope-type actuator when the supply pressures of 30 kPa is applied. From Fig. 2, it can be seen that the thickness of the actuator was greatly deformed about 39 times from the initial thickness of 1.5mm with no supplied pressure to maximum thickness of 58.4mm. By using typical laminate films and paper that can be easily got on the market as a stationery, the actuator can be quickly and easily fabricated. The time for production of the actuator is several minutes.

Fig. 2. View of movement of tested actuator (Left: no supply, Right: supply pressure of 30 kPa).

Fig. 3 shows the relation between the contracted displacement and the generated force of the actuator.

Fig. 3. Relation between the contracted displacement and the generated force of the actuator.

Fig. 3 shows the relation between the contracted length and the generated force of the actuator in the case when the supply pressure was applied every 5 kPa from 0 kPa to the maximum pressure (burst pressure). Further, the relation between the displacement and generated force of the actuator was investigated. From Fig. 3, it can be seen that the maximum generated force of 657 N could be obtained in the case of supplied pressure of 100kPa. From these results, the following experimental relation between the displacement and the generated force of the actuator can be obtained.

\[ F = A_0 P \left( 1 - \frac{A}{X_M} \right) \]  

where, \( F \), \( A_0 \), \( P \), \( A \), and \( X_M \) mean the generated force, equivalent sectional area, supplied pressure, displacement and maximum displacement of the actuator, respectively. In Fig. 3, the solid lines show calculated results using Eq. (1) with \( A_0=0.8L_A L_B=0.00792m^2 \) and \( X_M=2.9L_C=0.058mm \). From Fig. 3, it can be seen that the proposed experimental relation expressed by Eq.(1) about the generated force and displacement of the actuator can predict well the static characteristics of the tested actuator.

B. Multi-Chamber Type Thin Actuator

In order to increase the displacement of the actuator, it is better to use many actuators by laminating with parallel. However, this type actuator needs many supplied tubes. It makes the construction to be complex. Therefore we proposed and tested a multi-chamber type thin actuator that the actuators with single chamber are connected in series with pressure supply line.

Fig. 4 shows the view and construction of the multi-chamber type thin actuator that two envelope-type actuators with single chamber are connected in series. By using the stick shaped silicon rubber in the bypass, it is possible to supply air to both pressure chambers without any extra tube. The bypass using the silicon rubber can send supply air smoothly even if the actuator and the bypass are bent.

Fig. 4. Multi-chamber type thin actuator (Left: no supply, Right: supply pressure of 30 kPa).

Fig. 5 shows the transient view of the movement of the actuator using two multi-chamber type thin actuators. The actuator consists of two multi-chamber type thin actuators connected with four chambers in series. Both actuators are overlapped each other so as to make each actuator alternate. From Fig. 5, it is found that the actuator could be obtained a maximum displacement of 400 mm from the initial thickness of 15 mm. It corresponds about 27 times displacement of the original thickness. Furthermore, the working direction of the actuator can be held in the particular direction by overlapping each other alternately. The restricted directional motion of the actuator can be realized as follows. When the supplied pressure was applied to both thin actuators, by overlapping each other, two actuators twist so as to make rope shape. By this method, the stiffness of the actuator toward vertical direction becomes large according to the supplied pressure.

C. Analytical Model and Performance

Fig. 6 shows the model of the tested actuator. From the experimental results and geometric configuration of the actuator as shown in Fig. 1, the following relationships can be obtained. \( L_d=4.5L_C \), \( L_d=5.5L_C \), \( A_0=0.8L_A L_B \), \( X_M=2.9L_C \) where \( L_C \) is a half-length of the gusset as shown in Fig. 6. From (1) and these relations, the following equation can be obtained.
By using (2), we can design the thin actuator. An example of designing the actuator using (2) is as follows. In the design, we assume that the purpose of the design is “to determine the dimensions of one actuator which can generate the displacement of 300 mm when the load of 500 N is applied by using four-chamber type actuator”. From (2) in the case of \( F=500 \text{N}, \ X=300/4=75 \text{mm} \) and \( P=200 \text{kPa} \), the length \( L_{C} \) of 30mm is obtained. From these values, both lengths \( L_{A} \) of 135 mm and \( L_{B} \) of 165mm are obtained.

\[
F = 19.8PL_{C}^2 - 6.82PXL_{C} \quad (2)
\]

Fig. 7 shows the transient view of the movement of the redesigned actuator using these parameters mentioned above when the actuator turns the load of 490 N. From Fig. 7, it is found that the actuator could turn the concrete block of 490 N. The tested actuator also generates the larger displacement of more than 300 mm.

Fig. 8 shows the transient view of the movement of the actuator when it lifts up the concrete block of 520 N. As a result of this experiment as shown in Fig. 8, we confirm that the actuator has an ability of lifting up the load of 520 N. By using the proposed model, it is possible to easily design the actuator in order to get the desired generated force.

III. FLEXIBLE ACTUATOR USING LOW BOILING LIQUID

A. Low Boiling Point Liquid

In order to develop the actuator driven by low boiling point liquid, the boiling point of the liquid is very important from the viewpoint of the energy consumption and the response for heater. If the boiling point of the working liquid is higher, the larger electric power of the heater is required. In addition, from the viewpoint of working liquid in a rehabilitation device, it must have safety, non-toxicity to the human body and harmless to the environment. Therefore, we select a functional liquid (3M™ Co. Ltd., Novec™7000[9]) as a working liquid. Table I shows properties of Novec™7000. The liquid is a cleaning liquid for the electronic circuit board. The boiling point is 34 degrees centigrade. The liquid is nonflammable and nonpoisonous fluid virtually. The standard vapor pressure of 0.065 MPa is enough pressure to drive the envelope-type actuator. The high volume resistivity shows that the liquid can contact the electric heater directly during the high applied current.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Boiling point (°C)</td>
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</tr>
<tr>
<td>Freezing point (°C)</td>
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<tr>
<td>Vapor pressure (MPa)</td>
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<td>Steam latent heat (kJ/kg)</td>
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</tr>
<tr>
<td>Density (kg/m³)</td>
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<tr>
<td>Absolute viscosity (Pas)</td>
<td>4.5x10⁻⁴</td>
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<tr>
<td>Kinetic viscosity (cSt)</td>
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<tr>
<td>Surface tension (mN/m)</td>
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<tr>
<td>Refractive index</td>
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</tr>
<tr>
<td>Electrical strength (kV)</td>
<td>40</td>
</tr>
<tr>
<td>Volume resistivity (Ωm)</td>
<td>1x10⁴</td>
</tr>
</tbody>
</table>

B. Thin Flexible Heater

To install the heater into the envelope-type actuator, the heater must be flexible and thinner. Therefore, we proposed and tested a flexible thin heater using the functional paint that includes carbon nanotubes. Fig. 9 shows the view and schematic diagram of the tested thin flexible heater. The heater consists of copper tape as an electrode, a functional paint (Future Carbon GmbH Co. Ltd., Carbon e-Therm PUR-120)[10] and plastic laminate films. The production method of the heater is as follows. First, two copper conductive tapes are pasted on a laminated film. Next, the laminate film is coated with Carbon e-Therm. Before drying the paint (Carbon e-Therm), the paint is covered with the laminated film from both sides. The size of the heater as shown in Fig. 9 is 60 x 65 mm. The thickness of the heater is 0.5 mm. The heater has flexibility. By laminating the plastic films from both sides, the heater has durability even if the heater is bent.

Fig. 10 shows the relation between the input voltage and the reaching temperature of the tested heater. In the experiment, the temperature was measured by the infrared radiation temperature meter (Custom Co. Ltd., CT-2000D). From Fig. 10, it can be seen that the maximum temperature of heater reached more than 250 degrees with input voltage of 10 V. It was also found that the temperature of the heater increased according to input voltage.
voltage. The response time of the heater when the stepwise input voltage is applied is quite short, that is less than 1 second.

![Graph showing the relation between input voltage and reaching temperature of the tested heater.](image)

**Figure 10.** Relation between the input voltage and the reaching temperature of the tested heater.

C. **Flexible Actuator with Low Boiling Point Liquid**

Fig. 11 shows the construction of the flexible thin actuator with low boiling point liquid and flexible heater. The flexible heater is installed into the envelope-type actuator. To apply the voltage from the outside of the actuator, two copper tapes were connected with the heater. In the actuator, the low boiling point liquid with volume of about 50 cm$^3$ is also installed. The size of the actuator is 110 mm in length, 90 mm in width and 6 mm in thickness. The total mass of the actuator including the liquid is 80 g.

![Image of the construction of the flexible thin actuator with low boiling point liquid and flexible heater.](image)

**Figure 11.** Construction of the flexible thin actuator with low boiling point liquid and flexible heater.

![Image of the transient view of movement of the tested actuator.](image)

**Figure 12.** Transient view of movement of the tested actuator when the input voltage of 10 V is applied (Time: 5s, 10s, 15s).

Fig. 12 shows the transient view of the movement of the tested actuator when input voltage of 10 V was applied. Each figure shows the view of the actuator when 5, 10, 15 seconds from the beginning of starting to apply the voltage. It can be seen that the actuator reached at maximum displacement within 15 seconds. After stopping to apply the voltage, the actuator was contracted according to the decreasing the temperature of the liquid by natural cooling. We confirmed that the actuator did not make any sound during being driven.

![Image of the transient response of the displacement of the actuator.](image)

**Figure 13.** Transient view of movement of the actuator with cooler

IV. **CONCLUSIONS**

This study that aims to develop the wearable thin actuator driven by low boiling point liquid for portable rehabilitation device can be summarized as follows.

The flexible thin heater using the functional paint including carbon nanotubes was proposed and tested. The performance of the tested heater was also investigated. As a result, the maximum reached temperature of more than 250 degrees for immediately input voltage of 10 V could be obtained.

From view point of functionality and safety, the functional liquid Novect™7000 was selected as a working liquid of the actuator. By unifying the flexible heater and envelope-type actuator, the flexible thin actuator driven by fluidic power via electric power was proposed and tested.

The driving test of the proposed actuator was carried out. As a result, we confirmed that the tested actuator could be driven silently. We also confirmed that the tested actuator has suitable characteristics for portable rehabilitation device so as to return to its original shape after contracting it.
As our future work, the portable rehabilitation device using the tested actuators will be proposed and tested.

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REFERENCES


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