CONTROL PERFORMANCE OF A SPONGE-CORE-SOFT-RUBBER ACTUATOR FOR WELFARE MACHINES

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Abstract: In this paper, we investigate a new type of soft actuator to realize a human-friendly support device for welfare machines. The actuator is a flexible rubber actuator (called as a Sponge Core Soft Rubber Actuator) and its structure is a soft mechanism in which a sponge rubber is covered with silicone rubber. In addition to its actuation capability, the actuator can estimate external forces by making use of the relation between inner pressure and external force. Therefore, the actuator can be used as a hybrid element that has both actuator and force sensor functions. This paper discusses about the force control and sensing abilities of the actuator. Experimental results are presented to illustrate the practical effectiveness of the proposed hybrid element.

Introduction

In developed countries such as Japan, the demographic profiles of the population are undergoing drastic changes. The number of elderly people has been increasing rapidly, even as the share of younger people in the overall population has been declining. The resulting 'aging society' poses several long-term technological problems and challenges to researchers in robotics and rehabilitation engineering[1]~[5]. As the average age of caretakers rises, it is expected that more elderly people have to care for other elderly people. Moreover, the number of caretakers will decline, even as the number of those needing care increases significantly.

The above scenario calls for the design and development of support machines, which could (a) assist the elderly and physically weak in taking care of others, and (b) also autonomously provide care of the weak or elderly. Therefore, in order to develop human friendly support machines for elderly people, improvement of the interface between human and mechanical system has been becoming very important. Especially, soft mechanical interfaces are strongly required in motion assist machines for handicapped people or elderly people.

Therefore, an actuator that has both active elements and passive elements attracts attention to develop the soft mechanical interface. Thus, since pneumatic actuators have flexibility because of pneumatic compressibility, it is considered that pneumatic system is very useful to realize the above soft mechanical system.

In order to realize the system, we propose a new type of pneumatic soft actuator that a sponge rubber is covered with silicon rubber. We call it a sponge core soft rubber actuator. Especially, when we use silicon rubber as a coating material of sponge, we call it a silicon outer fence mold actuator. With respect to the actuator, since the sponge is coated with silicon rubber, air can be charged into the sponge chamber. As the results, it is possible to control the stiffness of the actuator by controlling pressure in the sponge chamber. Furthermore, since the actuator can realize a flexible motion according to external forces, the actuator can be attached to the body directory. This is because that the actuator is made of soft rubber material. Furthermore, the actuator can be driven by low pressure level. Therefore, we need a small size compressor to charge pressure in the actuator. Thus, it is easy to realize a compact pneumatic system by making use of the actuator. Moreover, it is possible to adjust an output force by controlling of pressure in the actuator. As the results, because of both force sensor ability and force control performance of the element, the actuator can be used as a hybrid type actuator.

In this study, we clear control performance of the actuator to realize a human friendly element for welfare machines.

Sponge Core Soft Rubber Actuator[6]~[7]

Structure of Actuator

In order to develop a hybrid element, we consider the pneumatic actuator design approach. The structure of the actuator is shown in Figure 1 (a). The actuator has two materials. One is silicone rubber and the other is sponge rubber. The sponge is coated with silicone rubber, and air can be charged into the sponge chamber. Since the actuator has two sponge layers, the actuator can expand as shown in Figure 1 (b).

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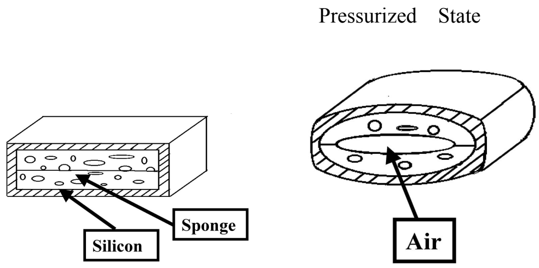
Sponge Plate Type

The actuator has sponge layer inside the silicone rubber. Therefore, when the actuator is made to burst by accident, the sponge material can support the subject by its inherent stiffness. As the result, the actuator can ensure safety for users.

Furthermore, in order to understand the performance aspects of the two layer-type actuator, we investigate the different sponge structures that are shown in Figure 2 (a)-(d). That is, the two-layer type actuator is tested with into four structures such as Type 1 (Standard type), Type 2 (Clipping type), Type 3 (Outer coat one layer type) and Type 4 (Outer coat one layer and clipping type).



(a) Initial State (b) Pressurized State

Figure1: Schematic View of the Actuator with Two Sponge Layers

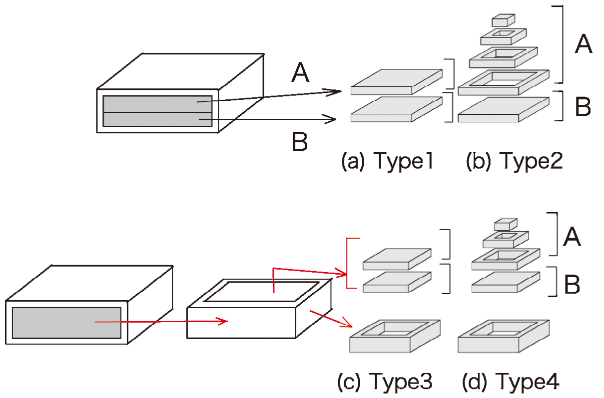


Figure 2: Structure of Sponge Plate

Force Control Performance

Step Response

In this section, we consider force control performance of the actuator with respect to each sponge type (Types 1~4). We investigate the dynamics of the actuator when air is charged into the sponge chamber. In the experiment, two types of sponges are used. One is a general polyurethane form (commercial name: ECZ) type with density of 16±1.5kg/m³ and the other is High hardness polyurethane form (commercial name: EMM) type with density of 52±3 kg/m³. The dimensions of the actuator are 80x80x20 mm. The experimental set up is shown in Figure 3. The pressure in the sponge chamber is measured by a pressure transducer. Further, we use a force sensor to measure the output force of the actuator.

First, we investigate the step response of force control. In the experiment, each type of sponge structure (Types 1-4) is investigated with respect to each type of sponge material (ECZ and EMM).

In the experiment, the hierarchical feedback control scheme [8] is applied to the force control of the actuator. The control equations are as follow. In the first step, the desired pressure is derived from Eq. (1). The input volt to the valve is calculated from Eq. (2).

$$P_r = K_P(F_r - F) + K_I \int (F_r - F)dt \qquad (1)$$

$$V = V_0 + K(P_r - P) \qquad (2)$$

P_r: Desired Pressure, F_r: Desired Force, V: Input Voltage to Valve, V_0: Neutral Voltage, K_P, K_I, K: Proportional, integral, and pressure gains.

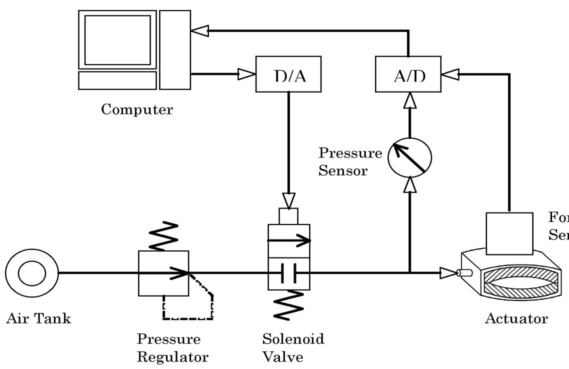


Figure 3: Experimental Setup

The experimental results are shown in Figure 4. In the cases of both ECZ and EMM, the target force is set at 5 N, which is attained satisfactorily with varying degrees of response speed depending on the type of sponge structure. The settling time and steady state error of each sponge type are shown in Table 1.

From the experimental results, it is clear that the result for Type 3 (sponge material: ECZ) is much better than the results for the other types. This is because the friction of clipping type elements (Types 2 and 4) is

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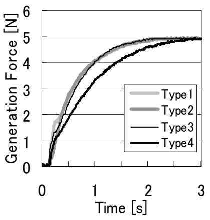
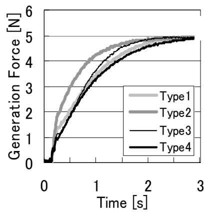
much larger than the flat plate type (Types 1 and 3). Further, in the case of Type 3 the deformation of the element is easier than the case of Type 1 because of the structure.



(a) ECZ

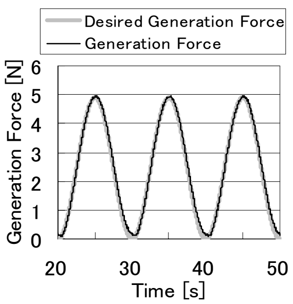


(b) EMM

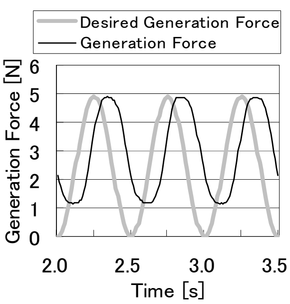
Figure 4: Experimental Results of Force Control

Table 1:Settling times and steady state errors

Type	Settling time, s		Steady state error, 10^{-3} x N	
	ECZ	EMM	ECZ	EMM
1	2.16	2.61	1.96	5.35
2	2.23	2.25	3.64	1.47
3	2.14	2.11	0.51	2.89
4	2.90	2.92	4.05	3.43



(a) f=0.1Hz



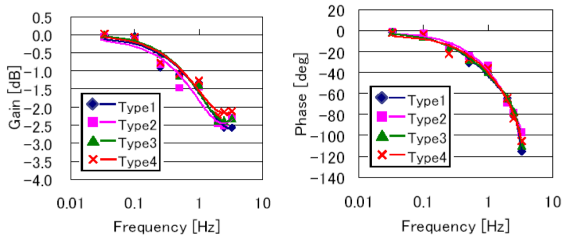
(b) f=2.0Hz

Figure 5: Experimental Results of Frequency Response with Force Control (ECZ-Typ 3)

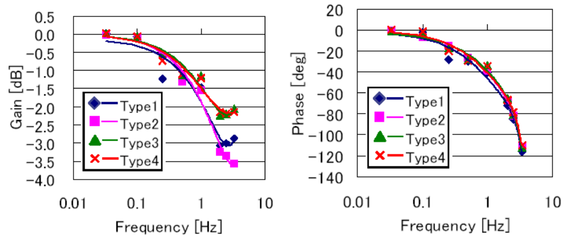
Frequency Response

In order to study the frequency characteristics of the actuator, we measure the output force corresponding to sinusoid pressure variation. The sample response of the experimental result in the case of Type 3 (ECZ) is shown in Figure 5 for two different frequencies. The corresponding Bode diagram showing the magnitude and phase of the force ratio [F/Fr] (F: Output force, Fr: Desired force) as a function of frequency is shown in Figure 6.

From these results, it is clear that with respect to the ECZ material there is almost no difference between the different sponge structures (Types 1 to 4). On the other hand, in the case of the EMM material the gains of Type 3 and Type 4 structures are much larger than those of Type 1 and Type 2 structures. Furthermore, when we use the Type 3 and Type 4 structures it is better to use these sponge types under 1Hz. From the results of both step response and frequency response, it is obvious that Type 3 is most useful to realize a good performance of force control.



(a) ECZ



(b) EMM

Figure 6: Bode Diagram

Force Sensing Performance

Force Estimation

In order to evaluate the performance of external force estimation, we use the Type 3 sponge structure as shown in Figure 2. Here, the sponge material is ECZ and the size of the actuator is 80x80x20 mm. The experimental setup is shown in Figure 7. In this experiment, air at an initial pressure P_0 is charged into the actuator. A force sensor is attached to the plate on the element (actuator) under the condition that the actuator is sealed up. At this time, we measure both inner pressure and compression force of the force sensor. The relation between the pressure in the actuator and force with respect to each initial pressure is shown in Figure 8. In the experiment, the initial pressure is varied from 0 to 9 kPa. From the experimental results, an external force estimation equation is derived as follows:

$$F = \frac{P - P_0}{\alpha_1 P_0^3 + \alpha_2 P_0^2 + \alpha_3 P_0 + \alpha_4} \quad \begin{pmatrix} \alpha_1 = -0.00008 \\ \alpha_2 = 0.0006 \\ \alpha_3 = 0.001 \\ \alpha_4 = 0.3004 \end{pmatrix} \qquad (3)$$

Here, F: External Force, P: Inner Pressure in the Actuator, P_0: Initial Pressure in the Actuator

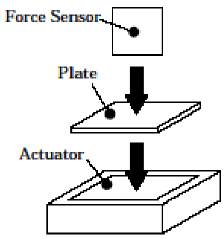


Figure 7: Experimental Setup

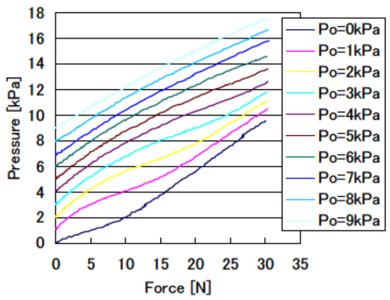


Figure 8: Experimental Results of Force Measurement

In order to verify the usefulness of Eq. (3), we measure the pressure in the actuator under the condition that a mass is placed on the plate of the element. At this time, the external force is calculated from Eq. (3). The results of external force estimation are shown in Figure 9. Here, the initial pressure is set at 6 kPa. From these results, it is clear that the average error is 0.44 N and maximum error is 1.03 N. Thus, the estimation equation is useful to estimate external forces.

Conclusions

In this paper, we have proposed a new type of hybrid element by using sponge core soft rubber actuator. By making use of the actuator, it is possible to realize a soft mechanism with human compatibility. Through several experimental results, the force control characteristics of the proposed element were illustrated. Furthermore, we clarified the capability for external force estimation of the element.

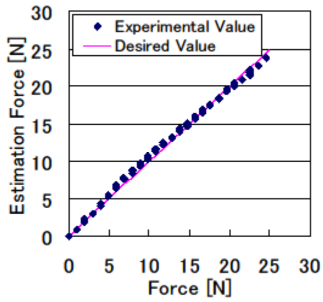


Figure 9: Experimental Results of External Force Estimation

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