DEVELOPMENT OF PORTABLE REHABILITATION DEVICE USING FLEXIBLE EXTENSION TYPE SOFT ACTUATOR WITH BUILT-IN SMALL-SIZED QUASI-SERVO VALVE AND DISPLACEMENT SENSOR

So SHIMOOKA*, Shujiro DOHTA *, Tetsuya AKAGI *, Wataru KOBAYASHI*, Masataka YONEDA*

* Department of Intelligent Mechanical Engineering, Okayama University of Science
1-1 Ridai-cho, Kita-ku, Okayama 700-0005, Japan
(E-mail: t14rm01ss@ous.jp, {dohta, akagi, kobayashi}@are.ous.ac.jp)

Abstract. Today, a welfare pneumatic equipment to support a nursing care and to execute a rehabilitation for the elderly and the disabled are actively studied and developed by many researchers. The total weight of a wearable device increases according to the degree of freedom of the device. In this study, we proposed a flexible extension type actuator with longer displacement. The maximum displacement of about 270 mm (235%) can be obtained. Using the actuator, the flexible robot arm was developed. As a result, we confirmed that the robot arm is able to extend straight and bend in any directions. An analytical model of the arm was proposed to predict the attitude of the arm. To control the actuator, the quasi-servo valve with built-in driving circuit using an embedded controller was also proposed and tested. In addition, the portable rehabilitation device using the robot arm, three quasi-servo valves and three displacement sensors was developed.

Keywords: Flexible extension type actuator, Built-in quasi-servo valve, Rehabilitation device, Wire type liner potentiometer

INTRODUCTION

Today, a welfare pneumatic equipment to support a nursing care and to execute a rehabilitation for the elderly and the disabled are actively researched and developed by many researchers[1-4]. The purpose of our study is to develop a home rehabilitation device that includes a controller, valves, sensors and actuators. In such a device, the total weight of a wearable device increases according to the degree of freedom of the device. Therefore, to decrease the burden of the user, a small-sized and light-weight pressure control type quasi-servo valve was developed in our previous study[5-6]. In the next step, we aim to develop a portable rehabilitation device with larger moving area which can give passive exercise for human shoulder[7]. To realize such a device with a compact configuration, it is necessary to develop an extension type actuator with a longer stroke[8]. In addition, to install a whole pneumatic driving system into the device, a built-in servo valve and flexible displacement sensor are also required[9-10]. In this paper, we propose and test a flexible extension type actuator with longer displacement. As a result, the maximum displacement of about 270 mm, that is more than 200% extension from original length, can be obtained when the input pressure of 400 kPa is applied. To control the actuator, the flow rate control type quasi-servo valve with built-in embedded controller is proposed and tested. Figure 1 shows an image of the proposed portable rehabilitation device. As shown in Fig. 1, we aim to develop a portable rehabilitation device giving a force to human arm and shoulder such as an expander and bender. The construction and operating principle of the device is described.

FIGURE 1. Image of the proposed portable rehabilitation device
EXTENSION TYPE SOFT ACTUATOR

Figure 2 shows the view and schematic diagram of the proposed flexible extension type actuator. The tested actuator consists of a rubber tube covered with a ruffled fabric sleeve. The rubber tube has an inner diameter of 6 mm, outer diameter of 9.5 mm and length of 200 mm. The original length of the ruffled fabric sleeve in the stretched condition is 450 mm. Figure 3 shows the relation between supply pressure and displacement of the actuator. In the experiment, the actuator was pressurized from 0 to 400 kPa every 20 kPa by using a pressure regulator. The measurement was carried out for three times. The maximum displacement of the actuator of about 270 mm, that is 235% extension of original length, can be obtained when the input pressure of 400 kPa is applied. It is also found that the hysteresis which is caused by the friction between the tube and the sleeve can be observed. In order to reduce the influence of hysteresis, it is necessary to execute a position feedback control using a flexible displacement sensor with a long stroke. The pushing force of the actuator while being pressurized is small because of its flexibility. However, the pulling force in case of decompression is large. It is an elastic force of the rubber tube. The maximum of pulling force is about 40 N.

![View and schematic diagram of tested flexible extension type soft actuator](image)

**FIGURE 2.** View and schematic diagram of tested flexible extension type soft actuator

![Relation between supply pressure and displacement of the actuator](image)

**FIGURE 3.** Relation between supply pressure and displacement of the actuator

FLEXIBLE ROBOT ARM

As a rehabilitation device with a wider moving area, a flexible robot arm using tested actuators as shown in Fig. 4 is proposed and tested. The robot arm consists of three extension type actuators with the original length of 200 mm arranged every 120 degrees at 30 mm from the center of the device. Both ends of the actuator are fixed with a triangle-shaped plastic plate. The device has 40 thin plates with the width of 1 mm to keep a parallel arrangement of three actuators and bending stiffness of the robot arm. The size of the robot arm is 230 mm in length, 90 mm in width and 90 mm in height. The mass of the arm is 420 g. Figure 5 shows the movement of the arm when three actuators are pressured. From Fig. 5, we can observe that the robot arm can bend in any directions by decompressing one or two actuators in three actuators.

![Overview of movement of flexible robot arm](image)

**FIGURE 4.** Overview of movement of flexible robot arm
In order to design and control the robot arm, an analytical model which can predict the characteristics of the robot arm is required. Figure 6 shows the analytical model of the flexible robot arm[11]. As shown in Figs. 6 (b) and (c), the flexible extension type actuator which is on X axis is defined as “actuator 1” and the other actuators arranged in a counter clockwise direction are defined as “actuator 2” and “actuator 3”, respectively. \(L_1, L_2, \) and \(L_3\) are the actuator length for actuator 1, actuator 2 and actuator 3, respectively. From the geometric relationship as shown in Figs. 6(b) and 6(c), the following equations can be obtained.

\[
L_1 = (R - r \cdot \cos \alpha) \cdot \beta, \quad (1) \\
L_2 = (R - r \cdot \cos\left(\frac{2\pi}{3} - \alpha\right)) \cdot \beta, \quad (2) \\
L_3 = (R - r \cdot \cos\left(\frac{4\pi}{3} - \alpha\right)) \cdot \beta, \quad (3) \\
R = \frac{L}{\beta} , \quad (4)
\]

where \(L\) means the central length of the robot arm, \(R\) is the radius of curvature of the arm, and \(r\) which is 30 mm is the distance between the center of the arm and the center of each actuator. \(\alpha\) and \(\beta\) mean the bending direction angle and bending angle, respectively. By using Eqs. (1) to (4), the central length of the robot arm \(L\), the bending direction \(\alpha\) and the bending angle \(\beta\) can be expressed as follows.

\[
L = \frac{L_1 + L_2 + L_3}{3} , \quad (5) \\
\alpha = \tan^{-1}\left(\sqrt{\frac{3(L_3 - L_2)}{L_2 + L_3 - 2L_1}}\right), \quad (6) \\
\beta = \frac{L - L_1}{r \cdot \cos \alpha} \quad (7)
\]

When \(\cos \alpha = 0\), the bending angle \(\beta\) can be obtained by the following equation from Eqs. (2) and (3).

\[
\beta = \frac{[L_3 - L_2]}{\sqrt{3}r} . \quad (8)
\]

From Eqs. (4) and (7), the radius of curvature of the arm \(R\) is given by

\[
R = \frac{L \cdot r \cdot \cos \alpha}{L - L_1} . \quad (9)
\]

When each actuator is pressurized, each length of the actuator \(L\) is given by

\[
L_i = L_{0i} + \frac{A(P_i - P_{\text{min}})}{k} , \quad (10)
\]

where \(L_{0i}, P_i, P_{\text{min}}, k\) and \(A\) mean the initial length of each actuator, supply pressure, minimum supply pressure (160 kPa), the elastic coefficient and the sectional area of the tube in an actuator, respectively.

Next, the calculated posture of the arm using above equations was compared with the experimental one. Figure 7 shows the comparison of the arm shape when the following pressure was given for each actuator. The supply
pressure $P_1$, $P_2$ and $P_3$ are 200 kPa, 400 kPa and 400 kPa, respectively. Figures 7(a) and (b) show the experimental result and calculated one, respectively. When the elastic coefficient $k$ is 345 N/m, the bending angle $\beta$ of 70 from Fig. 7(b) agrees with the experimental result. Figure 8 shows the relation between differential pressure and bending angle of the arm. The differential pressure means the pressure difference between $P_1$ and $P_2$ or $P_3$. The symbols show the experimental results and the lines show the calculated results. From Fig. 8, it is found that the calculated result does not agrees with the experimental result when the differential pressure is higher than 250 kPa. This is because the elastic coefficient $k$ changes with the supply pressure as shown in Fig.3.

(a) Analytical model of robot arm
(b) Definition of actuator length
(c) Definition of angles $\alpha$ and $\beta$

**FIGURE 6.** Analytical model of robot arm

(a) Experimental result
(b) Calculated result

**FIGURE 7.** Comparison of robot arm posture

**FIGURE 8.** Relation between differential pressure and bending angle

**QUASI-SERVO VALVE BUILT-IN EMBEDDED CONTROLLER**

Figure 9 shows the construction and the schematic diagram of the quasi-servo valve that we developed[12]. It consists of two standard on/off type control valves and an embedded controller. The output port of the first valve is connected to the input port of second one. The first valve is a three-port valve that can change the direction of fluid flow from the supply port to the output port or the fluid flow from the output port to the exhaust port. We call it a “switching valve”. The second valve is a two-port valve driven by PWM(pulse width modulation) method in order to adjust the valve opening per time. The PWM valve can adjust output flow rate like a variable
fluid resistance. In order to decrease the size and cost of the valve, the smaller-sized on/off control valve (SMC Co. Ltd., S070C-SDG-32) was used. Compared with the previous on/off control valve[6], the price of new valve is about a half, that is about 17 US dollars. The maximum flow rate of the valve is 8.5 liter/min when the supply pressure of 400 kPa is applied. This value of flow rate is enough to drive the flexible extension type actuator. As shown in Fig. 9, to realize the compact construction of connector between two on/off valves, the acrylic flow passages were used. The size of the valve without typical tube connector is 36x25x17 mm. The mass of the valve is only 24 g.

![Figure 9. Construction and schematic diagram of quasi-servo valve](image)

Figure 9 shows the construction and the schematic diagram of the tested flow rate control type quasi-servo valve with a built-in driving circuit using an embedded controller. The driving circuit consists of a tiny embedded controller (Renesas Co. Ltd., RL78/G10) and two transistors (Fairchild Semiconductor Co. Ltd., TO-92 2N7000). The flow rate control is done as follows. First, the embedded controller can get an analogue signal through A/D converter on the embedded controller. In the embedded controller, the input duty ratio is calculated based on the empirical formula[13]. The required input duty ratio is given through PWM port of the controller.

![Figure 10. Construction and schematic diagram of the tested flow rate control type quasi-servo valve with built-in driving circuit using an embedded controller](image)

Figure 10 shows the relation between the valve opening and the output flow rate of the tested valve. In the experiment, to measure the output flow rate based on the empirical formula[13] and to observe control parameters such as input normalized flow rate and output duty ratio, the embedded controller (Renesas Co. Ltd., SH7125) that has several serial communication ports was used. From the result shown in Fig. 11, the relation between the valve opening and output flow rate has a linear relationship. It means that the tested flow rate control type quasi-servo valve can change the sectional area of the valve linearly according to the control input.

![Figure 11. Relation between input valve opening and output flow rate](image)
PORTABLE REHABILITATION DEVICE

Figure 12 shows the overview of the control system of the portable rehabilitation device. The system consists of the tested robot arm, three quasi-servo valves with a built-in embedded controller, three wire type linear potentiometers[14] and a micro-computer (Renesas Co. Ltd., SH7125) for control the rehabilitation device. Even if the actuator bends, the sensor can measure the displacement of the actuator because the wire can move along to shape of the actuator through holes on thin plates. This sensor can also measure the long stroke of 210 mm. Figure 13 shows the schematic diagram of the control system of the portable rehabilitation device. The position control is done as follows. First, the wire type linear potentiometers measure each displacement of the actuators. The output value is taken by A/D converter in the micro-computer. The error between the desired and measured displacement is calculated by the micro-computer for control. The control input for the quasi-servo valve is also calculated based on the simple P control scheme. The control input for each valve is given as an analog signal from 0 to 5 V through D/A converter with SPI controller (Linear Technology Co. Ltd., LTC1660CN). In the quasi-servo valve, the built-in controller can control the valve opening (output flow rate) according to the input voltage based on the empirical formula as shown in Fig.11. In the case that the input voltage for the valve is higher than 2.5 V, the valve works as a supply valve. In the opposite case (lower than 2.5 V), the valve works as an exhaust valve. In the case of 2.5 V, the valve is closed. The valve opening is controlled according to the absolute value form 2.5 V. By this method, the attitude of the device is controlled. In the experiment, the reference displacement of 200 mm is given for each actuator. Then, the target value of 50 mm for the actuator is changed every 10 seconds.

Figure 14 shows the operation of attitude control for the portable rehabilitation device. Figure 15 shows the transient response of the displacement of the actuator. In the Fig.15, red line and blue line show the controlled displacement of the actuator and reference, respectively. It can be found that the controlled displacement agrees with the reference. This means that the device can follows up the target attitude well. In future work, we are going to develop a device which can give passive motions to patients who hold the device by hands like an active bender and expander.
FIGURE 14. Operation of attitude control for portable rehabilitation device

(a) Time: 100 s
(b) Time: 180 s
(c) Time: 260 s

FIGURE 15. Result of attitude control for portable rehabilitation device.

CONCLUSIONS

As a rehabilitation device with moving area, the portable rehabilitation device using extension type actuators was proposed and tested. As a result, we confirm that the tested actuator extends until more than 200% of original length. The flexible robot arm using the proposed actuators was proposed and tested. Also, in order to design and control the robot arm, the analytical model was proposed. As a result, it is confirmed that the calculated result does not agree with the experimental result when the supply pressure become higher. This is because the elastic coefficient change with the pressure. However, the calculated result shows the effect of the radius \( r \) on the bending angle well. To control the actuator, the flow rate control type quasi-servo valve was proposed and tested. The quasi-servo valve with built-in driving circuit using an embedded controller was developed. As an application, the portable rehabilitation device was tested. Also, in order to measure the displacement of the actuator, the wire type linear potentiometer was used in the device. As a result, it was confirmed that the controlled displacement agrees with reference. As future work, we will develop the device which can give passive motion to patients who hold the device by hands like an active bender and expander.
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