Development of 5–Port Type Low–Cost Servo Valve Using Buckled Tubes

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***Abstract*— Recently, wearable actuator for work assistance and rehabilitation, such as power assist suit, have received much attentions and studies have been done actively. In this study, the final target is to develop a low-cost home rehabilitation device driven by fluidic actuator using low-cost servo valve. In the device, the size and cost of control valves become serious concerns. In the previous study, a low-cost 3-port servo valve that was able to control the flow rate by changing the bending angle of the buckled tube was proposed and tested. In this paper, to drive a double acting type pneumatic cylinder by using one valve, 5-port type servo valve using bucked tubes is proposed and tested. To design the valve, the relation between the buckled tube length or buckled point and output flow rate of the valve is investigated. In addition, the position control system of the pneumatic cylinder using the tested valve is proposed and tested. Multi- position control of the cylinder is carried out. From the result, it can be confirmed that the tested valve can control the double acting type cylinder and the position control system is validated.**

***Index Terms*—servo valve using buckled tubes, control valve, 5-port type servo *valve*, position control**

I. Introduction

Recently, the wearable driving system has gained great attention and many studies have been carried out actively [1-4]. They have developed power assisting device for nursing care [1], elderly [2] and worker [3] using pneumatic artificial muscles [4]. In this study, the final target is to develop a home rehabilitation device driven by pneumatic or hydraulic actuators where users can afford it at a low price. In a fluidic driving wearable rehabilitation device, the size and cost of a control valve become serious concerns. Usually, the mainly expensive control device in the pneumatic and hydraulic driving systems is a servo valve. For example, a typical electro-magnetic servo valve has a complex and complicated mechanism for moving its spool while keeping a seal makes it to be expensive.

Therefore, the miniaturization and fabrication of a low-cost servo valve are our great challenge. To decrease its mass, size and cost, the simple mechanism for valve opening is required [5-10]. Zhao developed small-sized quasi-servo valve using small-sized on/off valve [5]. Many researches had developed a small-size valves which were driven by vibration such as piezoelectric actuator [6], sound [7,8] and a vibration motor [9]. In our previous study, a low-cost servo valve that was able to control the flow rate by changing the bending angle of the buckled tube was proposed and tested [11-14]. The position control of the pneumatic rubber artificial muscle using the valve was carried out [12]. The analytical model of the valve was proposed for optimal design [13] and the pneumatic and water hydraulic position control of the muscle using the valve were developed [14]. The valve can control the flow rate of both gas (air) and liquid (water). In this paper, to decrease the total cost of the driving system, 5-port type servo valve using bucked tubes that can drive a double acting type pneumatic cylinder is proposed and tested. In addition, to get the desired relationship between the output flow rate and the motor rotational angle of the valve, the static characteristics of the valve using some buckled tubes with various tube length and buckled point is investigated. The position control system of a typical pneumatic cylinder using the tested valve and an embedded controller is also proposed and tested. Multi-position control of cylinder will be carried out.

II. 3-Port Type Servo Valve Using Buckledtubes

A. Construction

Fig. 1 shows the construction of the 3-port type servo valve using buckled tubes developed in our previous study. This valve is aimed to improve maintainability of the valve. The tested valve consists of two buckled soft polyurethane tubes (SMC Corporation, TUS0425), two one-touch connecters (Koganei Corporation, US4M), a Y-shaped one-touch connecter (Koganei Corporation, UY4M), a small-sized RC servo motor (Asakusa Giken inc., ASV-15) with maximum speed of 480 deg./s, and an acrylic rotational disk with

connecter holders. Both one-touch connectors are used to hold the buckled tubes. The Y-shaped one-touch connector is used as a rotational output port. The rotational disk with Y-shaped one-touch connecter is connected with the motor shaft of the RC servo motor. The Y-shaped one-touch connector is connected to both buckled tubes for supply and exhaust. Two one-touch connecters are set to keep the initial angle of 63.4 deg. (that is a bending angle as shown Fig. 1) from Y-shaped one-touch connector at the neutral position of the RC

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servo motor. The angle was decided based on the previous study [14]. By using one-touch connectors, the buckled tubes in the valve can be easily changed. The mass of the tested valve is 39 g. The valve size is 57 mm in length, 79 mm in width and 46 mm in height. The valve can control the flow rate of both gas and liquid because of its simple changing mechanism of sectional area with no mechanical sliding parts.

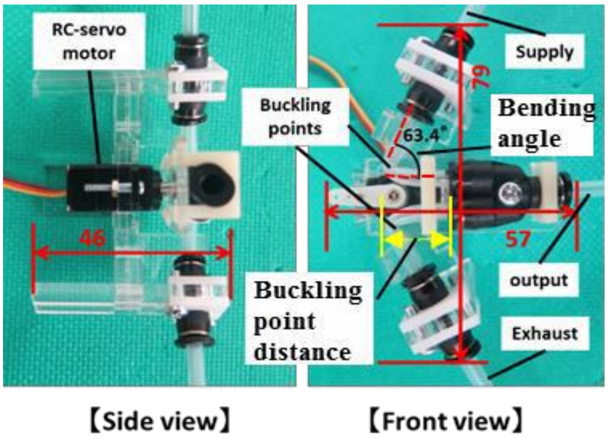

Figure 1. 3-port servo valve using buckled tubes.

B. *Operating Principle*

Fig. 2 shows the operating view of the valve. The operating principle of the tested valve is as follows: in the neutral position of the RC servo motor as shown in the left of Fig.2, the sectional area of both buckled tubes for supply and exhaust at the buckled point are zero, that is, both tube are closed. When the servo motor rotates clockwise as shown in the middle of Fig.2, the bending angle of the exhaust buckled tube is decreased and at the same time the bending angle of the supply buckled tube is increased. In this condition, the supply buckled tube has a certain sectional area that allows air pressure to pass through it while the exhaust tube is closed completely. The sectional area of supply tube is increased according to clockwise rotational angle of the RC servo motor. When the motor rotates counter-clockwise as shown in the right of Fig.2, the sectional area of supply port is decreased, and the sectional area of exhaust port is increased. Thus, the valve can control both of supply and exhaust flow rate by changing rotational angle of the motor.

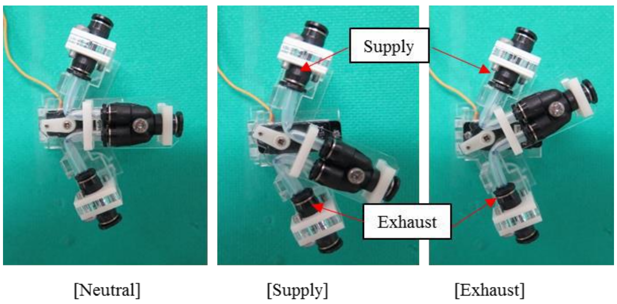

Figure 2. Operating view of servo valve using buckled tubes.

III. Influence of Buckled Tubes for Output Flow Rate Characteristics

The valves proposed in this study have good maintenance features, where buckle tubes can be replaced easily when there is a defect on it. However, the output flow rate characteristics of the valve is varied by the length and the buckled point of the buckled tube. Therefore, it is necessary to investigate the influence of shape parameters of the buckled tube for output flow rate characteristics. Figs. 3 to 5 show the relations between the motor rotational angle of the RC servo motor and the output flow rate of the tested valve using buckled point distance of 13, 14 and 15 mm, respectively. In the experiment, air supply pressure of 500 kPa is applied to the supply port in the valve through a pneumatic regulator from an air compressor. The buckled point distance is defined as a distance between the buckled point and the end of tube connected to the Y-shaped one-touch connector. Based on a previous study, the tube length of 48, 49, 50, 51 and 52 mm with the various buckled points of 13, 14 and 15 mm are used. These parameters decided based on the result of the preliminary test of the valve. In Figs. 3 to 5, each symbol shows the result using various length of buckled tube. It can be found that the all valves have overlap zone and it becomes larger in all buckled points as the length of the tube becomes longer. In addition, the maximum flow rate increases as the length of the tube becomes shorter. It can also be found that the overlapped zone and the gain (gradient) between the motor rotational angle and the output flow rate can be changed by adjusting the length of the buckled tube. The magnitude of the overlap zone influence the dynamic characteristics of the valve; the dead time of the valve. The dead time is the time until the motor rotational angle reaches the boundary angle of overlap zone from the neutral position (0 deg.). In the case using the tube with length of 50 mm and buckled point of 13 mm, the compensated value for dead time is 3 degrees. Therefore, from both views of dynamics related to smaller dead zone and statics related to the gain, the tube with length of 50 mm and buckled point of 13 mm is selected as an optimal value. In the next chapter, the construction and the operating principle of a novel 5-port type servo valve using buckled tubes with these optimal parameters will be introduced.

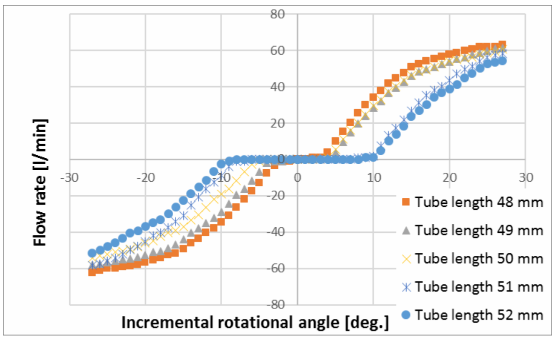

Figure 3. Relation between motor rotational angle and output flow rate of the valve using the tubes with buckled point distance of 13 mm.

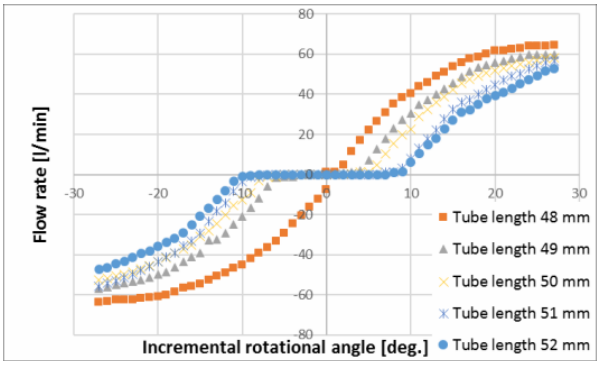

Figure 4. Relation between motor rotational angle and output flow rate of the valve using the tubes with buckled point distance of 14 mm.

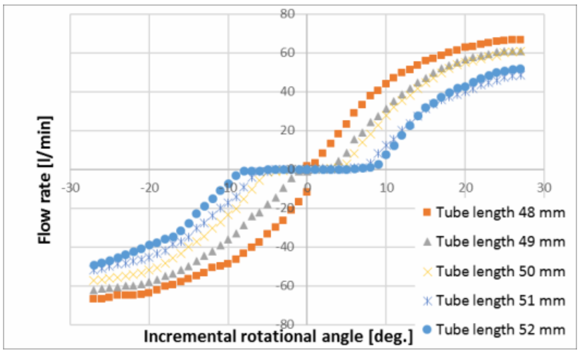

Figure 5. Relation between motor rotational angle and output flow rate of the valve using the tubes with buckled point distance of 15 mm.

IV. 5-Port Servo Valve Using Buckled Tubes

A. Construction

In order to drive a double acting type cylinder, two 3-port type valves are needed. In addition, to control the displacement and the generated force of the cylinder, the synchronized motion of two motors in both valves are required. In order to decrease the cost of the valves in the control system and complexity for synchronized motor motion, a 5-port type servo valve driven by one RC servo motor is proposed and tested. Fig. 6 shows the construction of the tested 5-port servo valve using buckled tubes. The tested valve consists of four buckled soft polyurethane tubes (SMC Corporation, TUS0425), four one-touch connecters (Koganei Corporation, US4M), two Y-shaped one-touch connecters (Koganei Corporation, UY4M), the same small-sized RC servo motor (Asakusa Giken Inc., ASV-15) and an acrylic rotational disk with connecter holders. Compared with the previous valve as shown in Fig. 1, two sets of buckled tubes and tube connectors for 3-port type servo valve are symmetrically located on the rotational disk each other. To prevent interference between two sets of buckled tubes, one set of connectors is placed with gap of 7 mm in height on the rotational disk. The gap can realize the compact configuration with symmetric arrangement of buckled tubes and connectors. The mass and size of the tested valve is almost same as the previous one. The mass of the valve is 73 g. The valve has a length of 90 mm in length, a width of 79 mm and height of 53 mm.

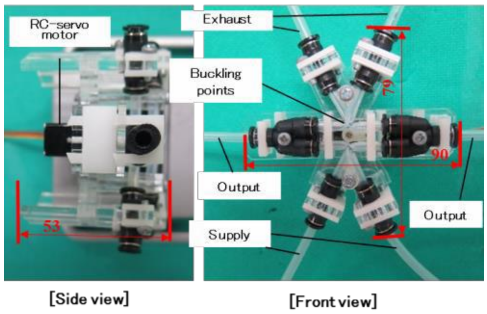

Figure 6. Construction of the 5-port valve.

B. Operating Principle

Fig. 7 shows the operating view of the tested valve. The operating principle of the valve is similar with the previous valve. Compared with the previous valve, the RC servo motor operates two 3-port type valves simultaneously. For example, when the servo motor rotates clockwise as shown in the middle of Fig. 7, the bending angle of left side exhaust buckled tube and right side supply buckled tube is decreased. At the same time, the bending angle of left side supply buckled tube and right side exhaust buckled tube is increased. The sectional area of left side supply tube and right side exhaust tube is increased according to clockwise rotational angle of the RC servo motor. It means that the left side output port works as a supply port and the right side output port works as an exhaust port by single rotational motion of the RC servo motor. In opposite case when the motor rotates counter-clockwise as shown in the right of Fig. 7, the left side outlet works as an exhaust and right side outlet works as a supply, respectively. The valve can also control the output flow rate from both output ports continuously. Thus, the valve can control both of supply and exhaust flow rate from two output ports synchronously by changing rotational angle of the motor.

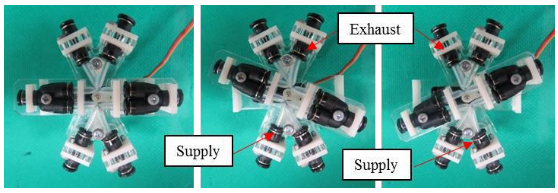

Figure 7. Operating view of servo valve using buckled tubes.

V. Position Control of Pneumatic Cylinder Using Tested Valve

A. Control System

In order to confirm the performance of the tested valve in controlling a double acting type pneumatic cylinder, the position control experiment of a typical pneumatic cylinder is carried out. Figs. 8 and 9 show the schematic diagram and the view of the position control system of the cylinder using the valve, respectively. The control system consists of the tested valve, a potentiometer (Midori Precisions Corporation, LP-100FJ), a pneumatic cylinder with an inner diameter of 16 mm and a stroke of 100 mm (Koganei Corporation, PBDA) and a micro-computer (Renesas Electronics Corporation, H8/3664F).

In Fig. 8, red and blue lines show the electric signal line and pneumatic power line, respectively. Two output ports of the valve connected to both inlets of the cylinder each other. The potentiometer is connected to the rod of the pneumatic cylinder in series to measure the cylinder displacement. The position control is done as follows. The micro-computer gets the output voltage from the potentiometer through 10 bit A/D converter as measured and desired values. The micro-computer calculates the deviation from the desired value. It also calculates an input duty ratio for the RC servo motor in the tested valve based on the control scheme and performs the position control of cylinder by controlling the valve. As a control scheme, the following simple discrete PID control scheme is used.

$$u(i) = k_P e(i) + k_D \big(e(i) - e(i-1)\big) + k_I \sum e(i) + D_C \mathrm{sign}(e(i)) \quad (1)$$

where, $u(i)$, $e(i)$, k_P, k_D, k_I and D_C mean the incremental change of duty ratio, the displacement error from the desired position, the proportional gain, the differential gain, integral gain and the compensator for overlap zone of the valve, respectively. i means the discrete time per 1 step and i-1 means the data before one sampling time. The input duty ratio for the servo motor is obtained by adding the initial duty ratio of the neutral position to the calculated $u(i)$. The proportional gain k_P of 0.302 %/mm, the differential gain k_D of 0.251 %/mm and integral gain k_I of 0.000251 %/mm are selected so as to decrease the tracking error by trial and error.

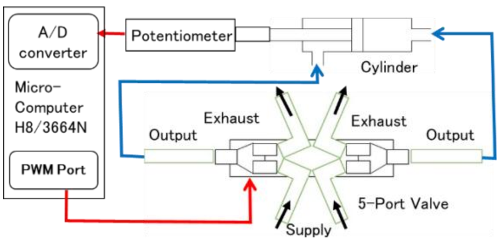

Figure 8. Schematic diagram of position control system using tested valve.

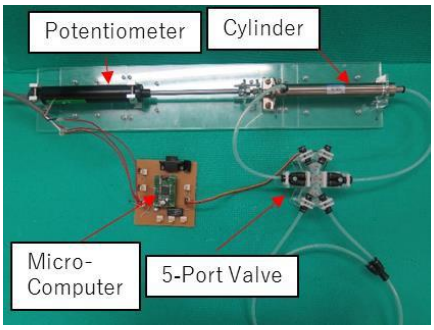

Figure 9. View of the position control system using tested valve.

B. Controlled Result

Fig. 10 shows the results of the multi-position control of the pneumatic cylinder. In the experiment, the supplied pressure of 500 kPa is applied to the valve. The desired positions of 50, 20, 80, 40 and 15 mm are changed every 2 seconds. The sampling period of the embedded controller (micro-computer) is 0.002 seconds. From Fig. 10, it can be seen that the pneumatic cylinder can trace the desired position well. Also, overshoot at the beginning of control seems to be caused by the lager operation quantity (flow rate) to overcome the static friction. The position control performance of the cylinder can be improved by applying the control scheme that compensates frictional force and time delay. As a whole, the controlled position can trace the desired position within standard deviation of 0.8 mm. As a result, it can be concluded that the tested 5-port type servo valve can operate and control the position of the double acting type cylinder by using only one valve.

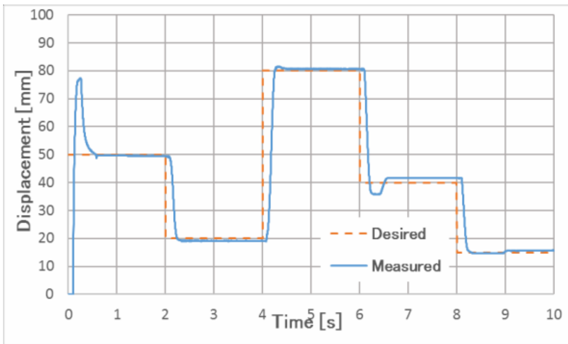

Figure 10. Position control result of pneumatic cylinder.

VI. Conclusions

This study aims to develop the low-cost servo valve used in home rehabilitation device can be summarized as follows.

To decrease the cost of the servo valves in the control system and to prevent the complexity for synchronized motor control of the valve while driving the double acting type actuator, 5-port type low-cost servo valve using buckled tubes was proposed and tested. To design the valve, the relations between the buckled tube length or buckled point and output flow rate of the 3-port type servo valve with various buckled tubes were investigated. As a result, it was found that the overlap zone became larger in all buckled points as the length of the tube became longer. It is confirmed that the buckled tube with length of 50 mm and buckled point of 13 mm is suitable to apply in the control valve from view point of static and dynamic characteristics of the valve.

Based on the result of influence of buckled tube, the low-cost 5-port type servo valve was proposed and tested. To confirm the performance of the valve, the position control of the typical pneumatic cylinder using the tested valve was carried out. As a result, the position control of the double acting type cylinder can be realized by using only one tested valve. It is also confirmed that the validity of the tested valve for driving double acting type fluidic actuator from the view point of reduction of required number of valves and simplification of valve controller.

As future work, it is necessary to apply the tested valve to a flexible wearable pneumatic actuator such as a flexible pneumatic cylinder. As the tested valve has an advantage that the valve can control both gas and liquid, the position control of the flexible water hydraulic cylinder will be carried out by using tap water pressure.

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