Improvement of Low-cost Wearable Servo Valve Using Buckled Tube

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In wearable pneumatic driving system, the small-sized and light-weight control valve and wearable actuator are important. Mostly, the total cost of control system depends on the cost of valves, because a popular industrial servo valve is very complex and expensive compared with a wearable actuator. The purpose of our study is to develop a small-sized and low-cost control valve that can be safe enough to be mounted on the human body. In our previous study, the low-cost servo valve using buckled tube was proposed and tested. However, the valve has relatively larger hysteresis in a relation between the motor rotational angle and output flow rate. In this paper, the improved servo valve with less hysteresis characteristics of output flow rate is proposed and tested. In addition, the configuration of the buckled tube on the valve is redesigned in order to reduce an overlap of the valve. Then, the improved valve is applied to the position control of the rubber artificial muscle. As a result, the position control performance of the muscle was also improved.

Keywords: Servo Valve, Control Valve, Welfare Equipment, Pneumatics, Mechatronics, Position Control

1. Introduction

Recently, wearable driving systems using pneumatic actuators for power assisted nursing care and rehabilitation have received much attention and many active researches have been carried out[1][3]. In such a control system, an actuator and a driving device such as a control valve are mounted on the human body[4][5]. As a wearable control valve drives pneumatic actuators to support the multi-degrees of freedom of human motion, the size and weight of the valve become serious problems. The typical electromagnetic solenoid valve drives its spool using a larger solenoid to open the flow passage. The solenoid valves also have a complex construction to keep a seal while the spool is moving. This makes its miniaturization and the fabrication of a low-cost valve more difficult. The purpose of our study is to develop a small-sized and lightweight servo valve that can be safe enough to mount on the human body at low cost. In our previous study, a low-cost servo valve using buckled tube was proposed and tested. However, the tested valve has a relatively larger hysteresis in a relation between the motor angle and the output flow rate of the valve. In order to improve the control performance of the pneumatic actuator driven by the proposed valve, a novel valve with the linear relationship with less hysteresis will be required. In addition, the improvement of dynamics of the valve will be also discussed in this paper by the method of decreasing the overlap of the valve.

2. Servo Valve Using Buckled Tube

2.1 Construction and Characteristics

Figure 1 shows the construction of the servo valve using buckled tubes in our previous study[6][7]. The valve consists of two buckled soft polyurethane tubes (SMC Co. Ltd. TUS0425: inner diameter of 2.5 mm, outer diameter of 4.0 mm), a small-sized RC servo motor (GWS Co. Ltd. PICO/STD/F rotational speed: 500 deg./sec), an acrylic valve holder and an acrylic tube holder disk. Two buckled tubes are used for supply and exhaust. The distance of each buckled tube is about 13 mm. Each end of the buckled tube is connected with each other as an output port. The initial twisted angle of the tube for supply port is set to 30 deg., while the initial twisted angle of the tube for exhaust port is set to 35 deg. These initial twisted angles can be obtained based on our previous work[7] in order to close both supply and exhaust ports in the initial condition.
**Figure 2** shows the operating principle of servo valve using buckled tube. The operating principle of the valve is as follows. Figure 2 (a) shows the valve in the initial condition when both of the supply and exhaust ports are open. When the servo motor rotates clockwise in Fig.2 (b), the twisted angle of exhaust tube is decreased and at the same time the twisted angle of supply tube is increased. By increasing the twisted angle of supply tube, the buckled point of the tube is deformed, that is twisted. The sectional area of the supply tube is increased according to the twisting angle. At the same time, the shape of the exhaust tube returns to the original shape of simple buckled tube. It makes the sectional area of the supply port is increased according to the twisting angle. At the same time, the shape of the exhaust tube returns to the original shape of simple buckled tube. It makes the sectional area of the supply port is increased, while the exhaust port is completely closed. When the servo motor rotates counter clockwise as shown in Fig.2 (c), the sectional area of supply port is decreased, while the exhaust port is starting to open. By this method, the valve can control both of supply and exhaust flow rate by the single motion of the motor. The mass of tested three-port type valve is 20 g, with the volume of 59 cc (46×40×32 mm). The mass and the size of the valve are suitable for a wearable device. The mass of the proposed valve is smaller than the typical small-sized servo valve such as FESTO MPYE-5-1/8-HF-010 B that has mass of 300 g.

Figure 3 shows a relation between the incremental rotational angle of the RC servo motor and the output flow rate of the tested valve. In Fig.3, the solid line shows the result in the case of increasing the rotational angle from -30 to 30 deg. The broken line shows the result in the case of decreasing in the rotational angle from 30 to -30 deg. This range of rotational angle of the servo motor was decided so that the twisted tube does not move to the opposite side. If the incremental rotational angle is over 30 deg., both supply and exhaust ports open at the same time. Both lines in Fig.3 show the average values from 4 times experimental results. From Fig.3, it can be seen that the hysteresis exists in the characteristics. We think that this hysteresis is caused by sliding the tube when the motor gives twisting motion to the tube. It can be also seen that the valve has an overlap between -3 and 8 deg. that can hold the output pressure. This function is very useful to control the pneumatic actuator from the view point of lower energy consumption.

2.2 Pressure Feedback Control to Compensate the Hysteresis

The tested servo valve has a hysteresis and non-linear characteristics in the relation between the angle of the servo motor and the output flow rate from the valve. In the case of applying a linear controller to the position control system using the pneumatic actuator such as an artificial muscle, these non-linear characteristics might cause the deterioration of the control performance of the valve. In order to solve this problem, we proposed and tested a pressure control type servo valve that output pressure from the valve can be always monitored and controlled by using an embedded controller and pressure transducer.

Figure 4 shows a schematic diagram of the pressure control system using the tested valve. The system consists of the tested valve, a pressure transducer (Panasonic Co. Ltd.
ADP5161), a micro-computer (Renesas Co. Ltd. H8/3664F), a potentiometer for desired pressure and a tank with a volume of 15 cc. The pressure control is done as follows. The micro-computer gets the output voltages from the potentiometer and pressure transducer through an A/D converter in the micro-computer: a desired and a measured value are detected. From two values, the micro-computer calculates the deviation from the desired value and performs pressure control in the tank by the three port type valve that is driven based on a proportional control scheme as shown by the following equation.

\[ d(i) = K_{pp} e_p(i) + 7.5 \]  

where, \( d(i) \) is the duty ratio to be applied to the servo motor, \( e_p(i) \) is the pressure deviation from the desired pressure and \( K_{pp} \) is the proportional gain. The additional value of 7.5 % in Eq.(1) is the value corresponding to the initial position of the servo motor. From the mechanical limitation of the servo motor, the input duty ratio \( d(i) \) will be used in the range between 4.4 and 10.6 %.

Figures 5 (a) and (b) show the transient response of the output pressure from the valve in tracking control for periodical desired pressure change. Both figures show the cases that the desired pressure is changed with a frequency of 0.5 and 1.0 Hz. In Fig.5, the broken line shows the desired pressure and the solid line shows the output pressure of the valve. The output port of the valve is connected to the tank with a volume of 15 cc. The control parameter such as a proportional gain was decided by trial and error so that the deviation could be decreased as small as possible. The proportional gain \( K_{pp} \) is 0.021 %/kPa. From Fig.5, it can be seen that the output pressure of the valve relatively can trace well to the desired pressure with lower frequency even if the simple control scheme is used. From the experiment of the pressure tracking control using the valve, the bandwidth frequency of 2.2 Hz was obtained. In addition, it can be also seen in Fig.5 (b) that the control pressure is decreased at about 350 kPa. This phenomenon is caused by the delay of the valve when the error is changing from positive to negative value.

The tested servo valve using buckled tube mentioned above used the micro-computer (Renesas Co. Ltd. H8/3664) as a controller. In order to decrease the estimated cost of the valve, the tiny micro-computer (Renesas Co. Ltd. R8C/M12A) whose cost is about 1 US dollar is suitable to construct the valve. The estimated cost of the flow control type servo valve using buckled tube is very low, that is about 9 US dollars. However, the cost of the pressure control type of the valve that includes the cost of the pressure transducer (Panasonic Co. Ltd. ADP5161: price is about 25 US dollars) is a little expensive, that is 34 US dollars. In addition, the control system using the pressure control type valve becomes more complex. If the valve with little hysteresis can be realized, it leads to produce the lower-cost rehabilitation device and wearable training equipment that can be used at home.

3. Improved Valve Using Buckled Tube

3.1 Construction and Characteristics

In order to decrease the hysteresis of the valve, to give the bending motion to the tube instead of the twisting motion is one of solution. However, the bending motion is required larger torque to the motor compared with the twisting type valve. Therefore, the suitable arrangement of two buckled
tube in the valve is investigated by changing the fixed position of the buckled tube and an initial buckled angle by trial and error while measuring the static characteristics between motor angle and output flow rate. From these experiments, the experimentally designed bending type servo valve could be obtained.

Figure 6 shows the construction of the improved servo valve using buckled tube. We call it “a bending type valve”. The previous valve is called as “a twisting type valve”. The bending type valve consists of a RC servo motor, two buckled tubes for supply and exhaust, an acrylic tube holder and rotary disk. Each end of the buckled tube is connected with each other as an output port. The supply and exhaust tubes are buckled at the position with the radius of 5 mm from the motor shaft. In the initial condition, the buckling tubes are held by the acrylic rotary disk so that each of the buckled angle is 65.7 deg. in clockwise and counterclockwise from the longitudinal axis of fixed tubes, respectively. Then, each end of the supply and exhaust port are fixed at the tube holder by passing through the smaller hole with the inner diameter of 3.8 mm set on the position with the radius of 20 mm from the motor shaft. The tubes are possible to slide along the suppressed plates on the rotary disk. This arrangement of both tubes that includes an initial buckling angle of 65.7 deg. and buckling point with radius of 5 mm from the motor shaft could be obtained from the experiment mentioned above. Compared with the previous valve, the buckled tubes in the improved valve are not twisted. The motor only gives the bending motion to both tubes toward the buckling direction. The alternative arrangement of two buckled tubes helps to decrease the reaction torque for the motor. It means that the reaction torques from two tubes are balanced in the initial condition. The operating principle of the improved (bending type) valve is almost same as the previous (twisting type) one. When the servo motor rotates clockwise, the buckled angle of exhaust tube is decreased and at the same time the buckled angle of supply tube is increased. Then, it causes the increasing of the sectional area in the supply tube by releasing the bending force at the buckling point, while the bending force acted on the buckling point of the exhaust tube is increasing. By increasing the buckled force, the exhaust tube closed surely.

Figure 7 shows the relation between the rotational angle of the servo motor and the output flow rate of the tested valves with supply pressure of 500 kPa. In Fig.7, the solid and broken lines show the results in case of increasing and decreasing the rotational angle, respectively. The red and blue lines show the cases using the twisting (previous) and bending (improved) type valves, respectively. From Fig. 7, it can be seen that the hysteresis characteristics using the bending type valve can be reduced compared with the case using the twisting type valve. In addition, by comparing with the overlap zone with the case using the twisting type valve that is -3 to +8 deg., we can confirm that the overlap zone becomes smaller with a range from -1 to +2 deg. The smaller overlap zone can be realized by changing the arrangement of two buckled tubes. By using the smaller overlap zone, the dynamics of the valve such as dead time will be improved.

Fig.6 Improved servo valve using buckled tube

Fig.7 Relation between rotational angle and output flow rate of the previous and improved valves

3.2 Pressure Feedback Control Using Bending Type Valve

Figures 8 (a) and (b) show the transient response of the output pressure from the bending type valve in tracking
control for periodical desired pressure change. The figures show the case that the desired pressure is changed with a frequency of 0.5 and 1.0 Hz. In Fig.8, the broken line shows the desired pressure and the solid line shows the output pressure of the valve. In the experiment, the same P control scheme is used. Compared with the previous results as shown in Fig. 5, it can be seen that the dynamics of the valve can be improved as shown in Fig.8. From these pressure tracking control results using the valve, the bandwidth frequency of 4.1 Hz was obtained.

![Frequency response of 0.5 Hz](image1)

![Frequency response of 1.0 Hz](image2)

The position control of rubber artificial muscle by controlling the valve based on a simple PD control scheme as shown in following equations.

$$u(t) = K_p e(t) + K_D (e(t) - e(t-1))/\Delta t$$  

$$d(t) = u(t) + 7.5$$

where, $e(t)$ is the deviation of the displacement from the desired position. $u(t)$ is the control input, $K_p = 0.088 [\%/\text{mm}]$ and $K_D = 0.000024 [\%\text{s}/\text{mm}]$ are the proportional and derivative gains, respectively. $d(t)$ is the duty ratio of the PWM signal input to the RC servo motor. $\Delta t$ is the control sampling period that is 1.9 ms. The additional value of 7.5 % in Eq.(3) is the value corresponding to the initial position of the servo motor. In the control, the dead zone in the range of

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3.3 Position Control of Rubber Artificial Muscle

In order to compare the performance of both valves, a position control of a rubber artificial muscle using both valves was carried out. Figure 9 shows a schematic diagram of a position control system. The system consists of the tested valve, a rubber artificial muscle (FESTO Co. Ltd. MXAM-10-AA), two potentiometers (Midori Precisions Co. Ltd., LP-50F) and a micro-computer (Renesas Co. Ltd., H8/3664F). The artificial muscle has a length of 254 mm, a stroke of 63 mm at a supply pressure of 500 kPa and an inner diameter of 10 mm at an initial condition. The position control is done as follows. The micro-computer gets the output voltages from two potentiometers through 10 bit A/D converter in the micro-computer: a desired and a measured value are detected. From two values, the micro-computer calculates the deviation from the desired value and performs the position control of rubber artificial muscle by controlling the valve based on a simple PD control scheme as shown in following equations.

$$u(t) = K_p e(t) + K_D (e(t) - e(t-1))/\Delta t$$  

$$d(t) = u(t) + 7.5$$

PWM signal input to the RC servo motor. $\Delta t$ is the control sampling period that is 1.9 ms. The additional value of 7.5 % in Eq.(3) is the value corresponding to the initial position of the servo motor. In the control, the dead zone in the range of
± 0.5 mm around the desired position is set to prevent the oscillation.

Figures 10 (a) and (b) show the transient responses of axial displacement of the rubber artificial muscle for tracking control using the twisting and bending type servo valves, respectively. In both control, same PD control scheme was used. In both figures, the broken lines and the solid lines show the desired and controlled displacement of the muscle, respectively. Compared with Figs.10 (a) and (b), it can be seen that the tracking control performance using the bending type valve is better than the case using the previous valve. It seems that the dynamics of the control system is improved by using the bending type valve from the view point of comparison of time delay.

Fig.11 Transient response of tracking displacement error of rubber artificial muscle

Figure 11 shows the transient response of the tracking error of displacement of the muscle. In Fig.11, the blue and red lines show the results using the twisting and bending type servo valves, respectively. The standard deviation of tracking error using the bending type valve is improved from 2.0 mm to 0.9 mm. We can conclude that the performance of the proposed valve is improved.

4. Discussion

The tested valve has some advantages that are small-sized, light-weight and low-cost. The valve also has no mechanical sliding parts in adjusting mechanism of sectional area where the working fluid contacts. In addition, the working fluid in the valve is quite isolated from dirty elements such as a lubricating oil, metal chips and static electricity. It means that the proposed valve can be used as a flow rate control valve of a medicine, flammable liquid and gas. From the operational principle of the valve, it is possible to control the flow rate even if either liquid or gas is used as a working fluid. In order to confirm this advantage, the flow control of the valve using tap water was carried out. Figure 12 shows the transient view of the flow control using tap water. In the experiment, the output flow rate of tap water is changed from the maximum to zero and from zero to maximum. From Fig.10, it can be seen that the tested valve can control the liquid as same manner as the gas. We confirm that the proposed valve has an ability to apply various fields such as a medical treatment, food production and water hydraulic system while keeping the production cost low. In addition, Fig.13 shows the experimental result of the relation between the opening area [mm²] and the buckled angle [deg.] of the tube. The result can be calculated from the measured flow rate of air with supply pressure of 500 kPa. By using this experimental result, the range of the output flow rate from the tested valve using various fluid can be predicted.

Fig.12 Transient view of flow rate control of tap water using the tested valve

Fig.13 Relation between buckled angle and opening area

5. Conclusions

The study aiming to improve the performance of the low-cost servo valve using the buckling tube was summarized as follows.

1) To improve the hysteresis characteristics of the previous servo valve using the buckled tube, the valve that acted the bending motion on two buckled tubes was proposed and
tested. The performance of the valve was investigated experimentally by changing the various design parameters such as an initial buckled angle and the buckled position of the tube. As a result, the suitable value of design parameter to get a linear relationship between the motor rotational angle and the output flow rate with narrow overlap zone was obtained.

2) To estimate the performance of the improved valve, the position control system of the rubber artificial muscle using the embedded controller was proposed and tested. The tracking position control was carried out. As a result, the standard deviation of position error was reduced from 2.0 mm to 0.9 mm.

3) As an application for water hydraulic valve, the flow rate control using tap water was executed. As a result, we concluded that the valve could control the flow rate of both gas and liquid even if the estimated cost of the valve is extremely low.

As our future work, the theoretical analysis of the tested valve will be carried out to predict the performance of the valve theoretically for the optimal design of the valve.

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