Improvement of a Pneumatic Control Valve with Self-Holding Function

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Abstract. The purpose of this study is to develop a small-sized, lightweight and low-cost control valve with low energy consumption and to apply it to the assistive system. We have developed some control valves; a tiny on/off valve using a vibration motor, and an on/off valve with self-holding function. We have also proposed and tested the digital servo valve with self-holding function using permanent magnets and a small-sized servo motor. In this paper, in order to improve the valve, an analytical model of the digital servo valve is proposed. And the simulated results by using the analytical model and identified parameters were compared with the experimental results. Then, the improved digital servo valve was designed based on the calculated results and tested. As a result, we realized the digital servo valve that can control the flow rate more precisely while maintaining its volume and weight compared with the previous valve. As an application of the improved valve, a position control system of rubber artificial muscle was built and the position control was performed successfully.

1. Introduction

Recently, it has been strongly desired to develop a system to aid in nursing care and to support the activities of daily life for the elderly and the disabled [1],[2],[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],[6]. When we consider to develop a wearable control valve that can drive pneumatic actuators to support the multi-degrees of freedom of human motion, the size and weight of the valve become serious problems. The typical electro-magnetic solenoid valve drives its spool with a large-sized solenoid. The solenoid valve has a complex construction to keep a seal while the spool is moving. This complexity makes its miniaturization and the fabrication of a low-cost valve more difficult. The purpose of our study is to develop a small-sized, lightweight, inexpensive control valve with lower energy consumption which can be mounted on the human body. We thought that the small sliding force to the spool can be useful to decrease the required force to open the valve compared with the longitudinal directional force as shown in Fig.1. In addition, it is possible to save the electrical power by utilizing the permanent magnet to drive the valve. Thus, our key concepts are summarized as follows:

1) The force from the side is applied to the ball to make a driving force smaller as shown in Fig.1.
2) The ball is set in the tube without any mechanical connecting part to realize “no sealing”.
3) The self-holding function is added by using permanent magnets to save the energy.

Figure 1(a) shows a construction of a simple check valve which consists of a ball, an orifice and a tube. For example, in a valve using ball diameter $D$ of 2 mm and orifice diameter $d$ of 0.5 mm, the...
horizontal force $f$ to open the valve is about a quarter of the longitudinal force $F$ as shown in Fig. 1(b).

Based on these concepts, we have developed two types of small-sized on/off control valve. One is the valve which can be driven by a small vibration motor [7]. Another is the valve which can be driven by an electromagnetic solenoid and a permanent magnet [8], [9]. Furthermore, we developed a digital servo valve which can adjust the output flow rate and pressure [10] described in the next section. The valve consists of some check valves, a cylindrical magnet and a tiny servo motor. This valve has an inherent problem: In order to control the flow rate more precisely, it is required to increase the number of check valve. However, it might make the valve larger and heavier. In this paper, therefore, we try to solve this problem and improve the valve. In addition, as an application of the improved digital servo valve, a position control system of rubber artificial muscle is built and tested. On the other hand, we have also developed an analogue type control valve using a buckled tube [11], [12]. This servo valve has some advantages; inexpensive, small-sized and applicable for any fluid.

![Figure 1. Construction of a check valve and required force](image)

(a) Construction of a check valve          (b) Required force to open a valve

2. Digital servo valve with self-holding function

Figure 2 shows the digital servo valve that includes four valves with self-holding function. The valve consists of a servo motor (GWS Co. Ltd., PICO/STD/F, speed: 500 deg./s), a disk with a cylindrical magnet and four check valves which consist of an orifice in the flexible tube with inner diameter of 2.5 mm and a magnetic ball with outer diameter of 2 mm. The center of the disk is connected with the shaft of the servo motor. The four check valves are set on parallel to the surface of the disk. The rotational angle of the disk is easily controlled by a micro-computer with PWM timer function. The mass of the tested valve is 22.5 g and the size is 24 x 36 x 50 mm. The operating principle of the valve is as follows. First, a cylindrical magnet stays at the neutral position as shown in Fig. 2(b). To increase the output flow rate from the valve, the servo motor rotates the disk from the neutral position to 40 degrees counterclockwise. The cylindrical magnet attracts the ball in the check valve. Then, the check valve 1 in Fig. 2 opens. By rotating the disk an additional 20 degrees (60 degrees from the neutral position) counterclockwise using the servo motor, the check valve 2 opens. At the same time, the ball in the check valve 1 loses the attracting magnetic force and the ball automatically moves toward the orifice by the momentum of the flow and closes the check valve 1. Then, the larger flow rate at the output port can be obtained according to the sectional area change from 1 to 2. In the same manner of increasing the output flow rate, the flow rate can be decreased by rotating the disk clockwise. The tested valve can realize five states that include holding the pressure and two types of flow rate in supply and exhaust.

![Figure 3. Relationship between valve opening and output flow rate](image)

Figure 3 shows the relation between the valve opening (state) and output flow rate from the valve. The valve opening is defined as the percentage to the maximum sectional area in the orifice diameter of 0.6 mm. The output flow rate was measured by a digital flow meter (SMC Corp., PF2A750-01-27). In the measurement of the supply flow rate, the supply pressure of 500 kPa is applied to the supply port in the condition that the output port is open to the atmosphere through the flow meter. In the case of measuring the exhaust flow rate, the output port is pressurized to 500 kPa in the condition that the supply ports are closed. From Fig. 3, it can be observed that the relation between the output flow rate and the valve opening is proportional in both cases of supply and exhaust states. In order to control the flow rate more precisely (multi-stage), it is required to increase the number of check valve; the number of orifice tube. However, the more the tube increases parallel on the surface of the disk, the larger the...
valve size becomes. Therefore, we try to locate the tube around the disk rotated by a servo motor three-dimensionally as shown in Fig.4.

(a) Construction  (b) Schematic diagram

Figure 2. Digital servo valve with self-holding function

Figure 3. Output flow rate

Figure 4. 3-dimensional arrangement

3. Analysis for improvement of the valve

3.1. Analytical model of the digital servo valve

In order to design the valve which can control the flow rate more effectively with limited number of check valve, we build an analytical model of the tested valve and investigate the optimal combination of the orifice diameter by simulation. Figure 5 shows an analytical model of the digital valve. The rotational angle of a servo motor $\theta_s$ is expressed as follows.

$$\frac{d\theta_s}{dt} = k_s \text{sign}\{\theta_s (t - L) - \theta_s\}$$  \hfill (1)

Where, $k_s$ and $\theta_r$ mean the rated angular velocity (=6.28 rad/s) and the reference angle, respectively. The dead time of the motor $L$ of 0.035 s is determined by experiment. The following equations are concerned with single check valve and the same equations can be applied to eight check valves. The relations between cylindrical magnet and steel ball can be obtained from the geometry in Figs.5 and 6, and they are given as follows.

$$\ell = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta_s}$$  \hfill (2)

$$r_i = r_{i0} - 0.5\left[ d_0 - D_b \sin (\theta_0 - \theta) \right]$$  \hfill (3)

Where, $\ell$, $r_1$, $r_2$, $r_{i0}$, $d_0$, $D_b$, $\theta_0$, $\theta$ represent the distance between cylindrical magnet and steel ball, distance between rotation axis and steel ball, distance between rotation axis and cylindrical
magnet, initial distance, inner diameter of orifice, diameter of steel ball, initial angle of steel ball and rotational angle of steel ball, respectively.

Figure 5. Analytical model for digital servo valve with eight check valves

The force acted on the steel ball by the cylindrical magnet can be expressed as follows.

\[
F_b = \begin{cases} 
0 & (\ell > \ell_{\text{max}}) \\
F_{b0} & (\ell \leq \ell_{\text{max}} \land F_b = 0 \rightarrow F_{b0}) \\
F_{b0}(t - L_b) & (\ell \leq \ell_{\text{max}} \land F_b = F_{b0} \rightarrow 0)
\end{cases}
\]

(4)

Where, \(\ell_{\text{max}} (=5.3 \text{ mm})\) is a critical distance which a steel ball and a magnet attract each other and can be determined experimentally. It is assumed that there is a dead time \(L_b\) when the attractive force \(F_b\) becomes from \(F_{b0}\) to zero. The dead time \(L_b\) of 10 ms and the constant force \(F_{b0}\) of 0.14 N are determined by simulation and experiment, respectively.

Figure 6 shows an analytical model for the opening of the valve. In the model, the steel ball rotates at the fulcrum C as shown in Fig.6. In the initial state of the ball (dotted line as shown in Fig.6), the ball has plugged up the orifice. The initial angle \(\theta_0\) is given by the following equation from geometric relation.

\[
\theta_0 = \sin^{-1}(d_o/D_b)
\]

(5)

The total torque \(\tau\) (a clockwise torque is positive) acted on the steel ball is the sum of the torques generated by the magnet, the differential pressure and the momentum of the fluid flow, and can be expressed as follows.

\[
\tau = \frac{D_b}{2} F_b \cos(\theta_0 - \theta) - \frac{\pi}{4} D^2_b \frac{d}{{d}^2 \theta} (P_a - P_s) - \frac{4}{\rho \pi} D^2_b Q_o^2 \frac{d}{dt} a_o
\]

(6)

The equation of rotational motion of the steel ball is given as follows.

\[
\frac{7}{5} m_b \left( \frac{D_b}{2} \right)^2 \frac{d^2 \theta}{dt^2} + C_b \frac{d \theta}{dt} = \tau
\]

(7)

Where, \(m_b\) and \(C_b\) mean the mass of the steel ball and the viscous drag coefficient of the ball. The opening area \(S_o\) of the valve changes with the angle \(\theta\) of the ball. In order to express this area simply, \(S_o\) is approximately given by the difference between the sectional area of the inner bore of the tube and the ball, and is expressed by the following equation.

\[
S_o = \frac{\pi}{4} \left( d_o^2 - D_b^2 \sin^2(\theta_0 - \theta) \right)
\]

(8)

The mass flow rates \(Q_o, Q_a\) as shown in Fig.7 are expressed as follows.

\[
Q_o = S_o P_o \sqrt{\frac{2}{RT}} \left( \frac{P_s}{P_a} \right)
\]

(9)
\[ Q_o = S_o P_o \sqrt{\frac{2}{RT}} f \left( \frac{P_a}{P_o} \right) \]  \hspace{1cm} (10)

Where, \( P_s, P_o, P_a, R \) and \( T \) represent the supply pressure, output pressure, atmospheric pressure, gas constant and absolute temperature, respectively. \( S_o \) can be expressed by same relation as Eq.(8). The function \( f(z) \) that expresses the state of flow state is given as follows.

\[
f(z) = \frac{\kappa}{\kappa - 1} \left( z^{2\kappa} - z^{\kappa(1)} \right) \hspace{1cm} (0.528 \leq z \leq 1)
\]

\[
f(z) = \frac{\kappa}{\kappa + 1} \left( 2 - z^{2(\kappa-1)} \right) \hspace{1cm} (0 \leq z < 0.528)
\]  \hspace{1cm} (11)

\[ \frac{dP_o}{dt} = \frac{\kappa RT}{V_o} (Q_o - Q_a) \]  \hspace{1cm} (12)

Where, \( \kappa \) and \( V_o \) mean the specific heat ratio (=1.4) and the volume of tank, respectively. By using equations from (1) to (12), we can calculate and predict the dynamics of the valve.

### 3.2 Identified system parameters and simulation

Table 1 shows the values of main system parameters. The optimal diameters of each orifice were obtained by simulation so that the pressure control by using the valve shows higher response and smaller steady state error. As a result, the following diameters were selected; \( d_1 = d_8 = 0.6 \text{ mm}, \ d_2 = d_3 = d_6 = d_7 = 0.3 \text{ mm} \) and \( d_4 = d_5 = 0.2 \text{ mm} \). The numbering of the orifice is shown in Fig.5.

| Parameter                  | Value    | Unit       |
|----------------------------|----------|------------|
| Viscous drag coefficient   | 0.6x10^{-6} | kg·m²/s   |
| Diameter of steel ball     | 2.0x10^{-3} | m         |
| Inner diameter of orifice  | 6.0x10^{-4} | m         |
| Inner diameter of tube     | 2.5x10^{-3} | m         |
| Mass of steel ball         | 3.3x10^{-5} | kg        |
| Initial distance           | 13.25x10^{-3} | m    |
| Distance                   | 8.75x10^{-3} | m         |
| Volume of tank             | 3.8x10^{-5} | m³        |
Figure 8(a) and (b) show examples of step response and frequency response of the output pressure, respectively. P control scheme is basically used. In both figures, chain line, solid line and broken line show the desired, simulated and experimental pressure, respectively. From Fig.8, it can be found that the pressure control can be realized and the simulated result agrees with the experimental result. We can confirm the validity of the proposed analytical model and the identified system parameters.

![Figure 8. Comparison of simulated result with experimental](image)

### 4. Improved digital servo valve and its application

#### 4.1 Improved digital valve

Figure 9 shows the improved digital servo valve. The valve consists of a servo motor, a disk with two cylindrical neodymium magnets (diameter of 4 mm, length of 5 mm) and eight check valves located parallel around the disk. The location angles of the tube are decided so that the total size of the valve keeps small and the valve does not open during a holding state. The size of the valve is 42 x 38 x 42 mm and the mass is 24 g. Compared with the previous valve, the improved valve has 4 more states although the volume and mass are almost same. In addition, the maximum flow rate of the improved valve is increased because of two cylindrical magnets. Figure 10 shows the relation between valve opening and output flow rate. The supply pressure is 500 kPa. It can be found that the output flow rate changes linearly and precisely with the opening in small openings. It can be also found that the maximum flow rate is increased to 25 lit/min compared with 16.5 lit/min of the previous valve.

![Figure 9. Overview of improved valve](image)

![Figure 10. Flow rate of improved valve](image)

#### 4.2 Position control of a rubber artificial muscle using the tested valve

As an application of the improved valve, we applied it to the position control of the rubber artificial muscle. Figure 11 shows a schematic diagram of the control system. The system consists of a tested valve, a rubber artificial muscle, two potentiometers and a micro-computer. The rubber muscle has a stroke of 63 mm and an inner diameter of 10 mm. The position control is done as follows. The micro-computer gets output voltages from potentiometers; desired and measured value and calculates the deviation from the desired position. Then, suitable check valves for supply and exhaust are selected to be opened based on the magnitude of the deviation. This means a quasi P control scheme. Figure 12
shows the transient response of axial displacement of the muscle. The blue chain line shows the desired position of 22 mm and red solid line shows the measured displacement. And the broken line shows the response using the previous valve. It can be seen that in the improved case, the dead time is a little smaller than the previous case, and the displacement is settled down the final position after 2 seconds. It can be concluded that the position control using the improved valve can give much better control performance than that using the previous valve.

Figure 11. Position control system

Figure 12. Transient response of displacement

In order to apply various control schemes to the tested valve, the relation between the valve opening (digital amount) and the valve opening (analogue amount; control input) should be described. Figure 13 shows the relation between both valve openings. For example, when the control input calculated by a control scheme is between 15 and 30%, the valve opening becomes 23% and the rotational angle of a servo motor becomes 28 degrees. Based on the relationship, the following PID scheme was applied to the position control of the muscle.

\[
 u(i) = K_p e(i) + K_i \sum e(i) \Delta t + K_d \frac{e(i) - e(i-1)}{\Delta t}
\]  

(13)

Where, \( u(i) \), \( e(i) \), \( K_p \), \( K_i \), \( K_d \) and \( \Delta t \) represent the control input, deviation of displacement, proportional gain, integral gain, derivative gain and sampling period for control, respectively.

Figure 14 shows the transient response of the displacement using above PID control scheme for several kinds of desired position. Each broken line shows the desired position and solid line shows the measured displacement. PID gains are tuned for the desired position of 20 mm : \( K_p = 5 \%/\text{mm} \), \( K_i =175 \%/(\text{mm} \cdot \text{s}) \) and \( K_d =10^{-5} \%/\text{s}/\text{mm} \). The sampling period \( \Delta t \) is 2 ms. It is found that the position control for different desired positions can be realized well.

Figure 13. Relation between valve openings

Figure 14. Transient response of displacement
5. Conclusions
This study on the pneumatic digital servo valve can be summarized as follows.
1) To improve the previous digital servo valve, an analytical model of the valve is proposed. And the optimal combination of the orifice diameter is investigated by the simulation. As a result, the validity of the proposed model is confirmed by comparing the calculated results with the experimental. And the optimal combination of orifice was obtained.
2) Based on the results of simulation, the improved valve was produced and tested. And it was applied to the position control of the rubber artificial muscle. As a result, it was confirmed that the improved valve can control the flow rate and pressure more precisely than the previous valve while keeping its volume and mass. And the position control using the improved valve can give much better control performance than that using the previous valve.

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