Control and analysis of robot arm using flexible pneumatic cylinder

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Abstract

The main characteristics of robot are the precision work with a high degree of reliability and the repetitive over long period that makes it suitable for use in the medical field. In this paper, the control and analysis of robot arm for the human wrist rehabilitation by using flexible pneumatic cylinder is introduced. The system consists of a slave arm, a master arm, a high-speed microcomputer, compact and inexpensive quasi-servo valves, a potentiometer and accelerometers to give the references for the attitude control. The robot arm has three degrees-of-freedom that is bending, extending and contracting. The control performances of the robot arm were investigated and the analytical model of the whole robot arm system including the flexible pneumatic cylinder, the quasi-servo valves and an embedded controller was proposed and tested for estimating the performance theoretically. We also made comparisons between the calculated and experimental results to confirm the validities of the proposed model and the identified system parameters. The results from experiments show that the proposed models accurately predict the behavior of the tested flexible robot arm using flexible pneumatic cylinders. The proposed master-slave control system has a potential for application for robot-assisted rehabilitation and training especially for human wrist.

Key words : Pneumatic robot arm, Flexible pneumatic cylinder, Rehabilitation device, Master-slave control, Analytical model, On/off control valve

1. Introduction

The growing elderly population continues to rise while birthrates continue its decline. This is a problem many countries are currently facing. The problem is especially serious when a society and its representative government fail to provide the appropriate social services to its aging and disabled population. This problem can be encountered in Japan. People over the age of 65 in Japan accounted for 24.1% of the total of population in 2012, (Ministry of Internal Affairs and Communications, 2013). These numbers continue to increase year after year and are raising the concerns of professionals from a variety of fields including the social sciences, medicine and engineering. Nowadays, many studies have shown that robots can be beneficial to healthcare providers in a variety of ways from supporting in lifting patients, (Ishii, et al., 2005) to performing complex surgical procedures, (Piquion, et al., 2009). The capacity of doing precision work reliably and repetitively for long periods would be of great value in this field. They can be used to assist in nursing care, (Nagata, 2004) and also can support the activities of daily living for people with disabilities, (Noritsugu, et al., 2009). However, it must also have safety features as to not cause harm to users and to have a flexible structure so as to be used and operated by human touch, (Kobayashi, et al., 2004). In recent years, many lightweight actuators have been studied and developed. The materials used for the actuators presently in use have also been studied in order to develop portable versions which can be conveniently transported anywhere. Cost for producing actuators and robots must be also taken into consideration. So far we have proposed and tested the new types of the flexible pneumatic actuator using low-cost embedded controller in our laboratory. The flexible robot arm has been also proposed and

tested in our studies for rehabilitation of the human wrist. This robot arm with simple structure by using rod-less type flexible pneumatic cylinders has three degrees-of-freedom: bending, extending and contracting, (Fujikawa, et al., 2010). From the view point of easy force control by adjusting the applied pressure, safety, human-friendly, compact construction and lightweight, we believe that this flexible mechanism has a potential for applications in rehabilitation and training. The master-slave control is adopted into the robot arm as a control method in order to be used in rehabilitation field. In this paper, first, the construction and operating principle of the flexible pneumatic cylinder and robot arm are explained briefly. Then, the analytical model of the whole robot arm is proposed. This includes the analytical models of a quasi-servo valve, the flexible pneumatic cylinder and the flexible robot arm. And the master-slave control system of the robot arm and its control procedure are described. Finally, the calculated results using the proposed model and the identified system parameters are compared with the experimental result.

2. Flexible Pneumatic Cylinder and Robot Arm

2.1 Flexible Pneumatic Cylinder

Figure 1 shows the construction of the flexible pneumatic cylinder. The flexible pneumatic cylinder consists of a flexible tube, two types of steel balls that have diameters of 9 mm and 3 mm, brass rollers and a slide stage. The flexible tube as a cylinder which allows air to pass through it is made of the soft polyurethane tube (SMC Co Ltd, TUS 1208). The 9 mm steel ball as a cylinder head is pinched by two pairs of brass rollers from both sides. This allows the ball to move freely when air enters into the cylinder. 3 mm steel balls are inserted between the slide stage and the flexible tube to hold the cylinder and brass rollers and at the same time to enable natural movement for the tube.

Fig. 1 Construction of the flexible pneumatic cylinder

The operating principle of the flexible pneumatic cylinder is as follows. When the pressure is applied from one end of the flexible tube, the 9 mm steel ball which is in the middle of the slide stage is pushed and moved accordingly. At the same time, the steel ball pushes the brass rollers and then the slide stage moves while it deforms the tube. The slide stage will move to the right side when the pressure is supplied at the left side end of the flexible tube. By using various center distance D and distance W between two pairs of rollers as a design parameter, the optimal combination between D and W so that the driving pressure of the pneumatic cylinder becomes minimum had been investigated by the experiment. The result shows that the best value for D is 14.4 mm and W is 10 mm, (Akagi and Dohta, 2007). In this combination, the frictional force of the slide stage is small and the 9 mm steel ball does not get out from the slide stage.

2.2 Flexible Robot Arm

Figures 2 (a) and (b) show the structural diagram and overview of the flexible robot arm using flexible pneumatic cylinders, respectively. The robot arm consists of two round stages: an upper and a lower, three flexible pneumatic cylinders, an accelerometer, a potentiometer and three slide stages, (Aliff, et al., 2012). The outer diameter of the upper and lower stage is 100 mm and the length of cylinder tube is 250 mm as shown in Fig. 2 (a). Each flexible pneumatic cylinder is arranged so that the central angle of two adjacent slide stages becomes 120 degrees on the stage. An end of each flexible cylinder is fixed to the upper stage. Two on/off control valves (Koganei Co. Ltd., G010HE-1) or quasi-servo valves, (Moriwake, et al., 2012) are used to drive one flexible pneumatic cylinder. In order to control the three flexible cylinders, six control valves are needed. The basic operating principle of the flexible robot arm is as

follows. To make the arm extend or contract, pressure must be applied on one end of the cylinder only. The robot arm will extend or move upward if the pressure is applied on the three upper ends of the cylinders. On the other hand, the robot arm will contract or move downward if the pressure is applied on the three bottom ends of the cylinders. To perform a bending motion to the right, for example, the right cylinder requires pressure from both ends to limit movement while the remaining two cylinders require pressure from the top to enable movement. The robot arm will bend by constricting one cylinder and extending the others. The upper round stage moves in the range of 0 to 180 mm with three cylinder tubes.

Fig. 2 Flexible robot arm

3. Analytical Model of Robot Arm Control System

3.1 Analytical Model of Control Valve and Flexible Pneumatic Cylinder

In order to improve the control performance of the robot arm by using the flexible pneumatic cylinders that is mentioned above, it is necessary to analyze the control valve and the cylinder. The theoretical approach using analytical models of the whole position control system that includes the flexible pneumatic cylinder, quasi-servo valves and the embedded controller with sampling frequency and A/D converter is also required. Figure 3 shows the analytical model of control valves and flexible pneumatic cylinder. Figure 3 (a) shows the model of the on/off valve used in the quasi-servo valve. In our previous study, the precise analytical model of the quasi-servo valve that includes the models of the on/off valve had been proposed and tested, (Zhao, et al., 2010). We had also confirmed the validity of the proposed model by comparing the experimental result and the calculated result using the model and the identified parameters. Therefore, we propose a model of a whole position control system using flexible pneumatic cylinder with two quasi-servo valves and the embedded controller. Figure 3 (b) shows the analytical model of the flexible pneumatic cylinder with two quasi-servo valves. In Figs. 3 (a) and (b), the characters A , D , M , P , Q , V , x and y mean the sectional area, the frictional force, mass, pressure, mass flow rate, volume, spool displacement and displacement of the slide stage, respectively. Each subscript shows the location. A detailed model of the quasi-servo valve is given by our previous work, (Zhao, et al., 2010).

Since there are two kinds of flow to the flexible cylinder such as the forward and backward flow as shown in Fig. 3 (b), it is necessary to divide two cases with respect to the pressure in quasi-servo valve P_o and pressure in flexible pneumatic cylinder P_F . Then, the next equation can be obtained.

If $P_{oj} \geq P_{Fj}$ (forward flow),

$$Q_{Fj} = A_{pj} P_{oj} \sqrt{\frac{2}{RT}} f(z) \quad , \quad z = \frac{P_{Fj}}{P_{oj}} \quad (1)$$

If $P_{oj} < P_{Fj}$ (backward flow),

$$Q_{Fj} = -A_{pj} P_{Fj} \sqrt{\frac{2}{RT}} f(z) \quad , \quad z = \frac{P_{oj}}{P_{Fj}} \quad (2)$$

where R , T and $f(z)$ mean a gas constant, an absolute temperature and a function which depends on the state of fluid flow, respectively. The subscript j means the right or left cylinders or valves as shown in Fig. 3(b).

Fig. 3 Analytical model of control valves and flexible pneumatic cylinder

If a change of pressure in both chambers of the flexible cylinder is assumed as an adiabatic change, the following equation for each pneumatic cylinder can be obtained.

$$\frac{dP_{Fj}}{dt} = \frac{\kappa RT}{V_{Fj}} Q_{Fj} - \frac{\kappa P_{Fj}}{V_{Fj}} \frac{dV_{Fj}}{dt} \quad (3)$$

where chamber volume V_{Fj} is given by the following equations.

$$V_{FL} = V_{FLo} + A_F y \quad (4.1)$$

$$V_{FR} = V_{FRo} - A_F y \quad (4.2)$$

where V_{FLo} and V_{FRo} mean the initial volume of the cylinder chamber. The motion equation of the slide stage as shown in Fig. 3(b) is given by the following equation.

$$M_s \frac{d^2 y}{dt^2} = A_F (P_{FL} - P_{FR}) - C_F \frac{dy}{dt} - D_f \quad (5)$$

where the non-linear frictional force D_f is divided to the static friction and Coulomb's friction, and both frictions are given as follows:

When $\left| \frac{dy}{dt} \right| \leq \varepsilon_v$,

$$D_f = A_F (P_{FL} - P_{FR}) * \operatorname{sgn} \left(\frac{dy}{dt} \right) \quad \left(\left| A_F (P_{FL} - P_{FR}) \right| \leq F_s \right) \quad (6.1.a)$$

$$D_f = F_s \operatorname{sgn} \left(\frac{dy}{dt} \right) \quad \left(\left| A_F (P_{FL} - P_{FR}) \right| > F_s \right) \quad (6.1.b)$$

When $\left| \frac{dy}{dt} \right| > \varepsilon_v$,

$$D_f = F_c \operatorname{sgn} \left(\frac{dy}{dt} \right) \quad (6.2)$$

where M_s , C_F , D_f , F_c , F_s and ε_v mean the mass of the slide stage, viscous damping coefficient, the frictional force, Coulomb's friction, static friction and the threshold speed between the static and Coulomb's friction, respectively. In the flexible robot arm as shown in Fig. 2, the slide stage of the cylinder is fixed to the lower round stage while the upper round stage can execute movement. In such case, Eq. (5) can be modified as follows.

$$M_F \frac{d^2 y}{dt^2} = A_F (P_{FL} - P_{FR}) - C_F \frac{dy}{dt} - D_f \quad (7)$$

Where M_F is the mass of the tube and round stage. By using Eqs. (1) to (7), we can predict the motion of the slide stage or the cylinder tube.

3.2 Analytical Model of Robot Arm

Figure 4 shows the analytical model of robot arm. As shown in Figure 4 (a) and (b), the shape of the flexible pneumatic cylinder is assumed to always be a circular arc when the robot arm is curved. Figure 4 (a) shows the definition of the angle and the bending angle of the curved direction of robot arm. From the centre of the robot, the angle from the X axis is a bending direction angle α , while the bending angle β is defined as the angle between the normal vectors from the centre of the upper surface of the Z axis of the robot arm. Fig. 4 (b) shows the pneumatic flexible cylinder which is on the X axis is marked as cylinder 1, when viewed from above the robot arm, the cylinders which are arranged in a counter clockwise direction are marked as cylinder 2 and cylinder 3. L_1 , L_2 and L_3 are the cylinders length for cylinder 1, cylinder 2 and cylinder 3, respectively. Where L means the length of a central tube installed between the upper and lower round stage and R is a radius of curvature of the cylinder. From the geometrical relationship as shown in Fig. 4 (b), the lengths of each cylinder are given by the following equations.

$$L_1 = (R - r \cdot \cos \alpha) \cdot \beta \quad (8)$$

$$L_2 = \left\{ R - r \cdot \cos \left(\frac{2\pi}{3} - \alpha \right) \right\} \cdot \beta \quad (9)$$

$$L_3 = \left\{ R - r \cdot \cos \left(\frac{4\pi}{3} - \alpha \right) \right\} \cdot \beta \quad (10)$$

$$R = \frac{L}{\beta} \quad (11)$$

Fig. 4 Analytical model of robot arm

Figure 5 shows the analytical model of the overall robot arm which consists of three flexible pneumatic cylinders, two round stages and six quasi-servo valves. Valve *U* and valve *L* represent the upper valve and lower valve for each cylinder, respectively. In the modeling, the following assumptions are used.

1. The interference force between cylinder tubes can be neglected.
2. The moment of inertia of the robot arm while the round stage is moving can be ignored.

Assumption 2 is based on the fact that the robot arm does not move so fast as shown in Fig. 10.

Fig. 5 The analytical model of overall robot arm which consists of three flexible pneumatic cylinders and 6 quasi-servo valves

In order to realize the simulation of attitude control of the robot arm, α , β and R must be expressed by using the length of the cylinder (L_1 , L_2 , L_3). The length of the central tube L is given by

$$L = (L_1 + L_2 + L_3) / 3 \quad (12)$$

By using Eqs. (8) to (11), the bending direction angle α and the bending angle β can be obtained as follows.

$$\alpha = \tan^{-1} \frac{\sqrt{3}(L_3 - L_2)}{L_2 + L_3 - 2L_1} \quad (13)$$

In the calculation, the case where the denominator equals zero is considered by using the function of atan2. And when the numerator is negative, 2π is added to the value calculated by Eq. (13) so that the value of α will be in the range of 0 to 2π .

$$\beta = \frac{L - L_1}{r \cdot \cos \alpha} \quad (14.1)$$

When $\cos \alpha = 0$, from Eqs. (9) and (10), it can be seen that β is calculated by following equation.

$$\beta = \frac{|L_3 - L_2|}{\sqrt{3} \cdot r} \quad (14.2)$$

From Eqs. (11) and (14.1), the radius of curvature of the cylinder R can be obtained as follows.

$$R = \frac{L \cdot r \cdot \cos \alpha}{L - L_1} \quad (15.1)$$

When $\cos \alpha = 0$, then $L - L_1$ becomes zero from Eq. (8). At that case, by using Eqs. (11) and (14.2), the following equation can be obtained. In the Matlab Simulink calculation, the case when the absolute value of the denominator is less than 0.0001 m, the denominator is set to 0.0001 m.

$$R = \frac{\sqrt{3} \cdot rL}{|L_3 - L_2|} \quad (15.2)$$

By using Eqs. (1) to (15) under above assumptions, the behavior of the robot arm control system can be predicted. Its control system and control procedure are shown in the next section.

The proposed analytical model includes the dynamics of three cylinders with upper round stage, the dynamics of six quasi-servo valves and the dynamics of fluid flow in the pipes and the cylinder tubes. These models can be used to improve the control performance of the system.

On the other hand, the proposed analytical model does not include the generated torque and the influence of the external force on the robot arm. However, the generated force and torque at the arm end can be modeled by utilizing Eq. (7). Then the stiffness control of the robot arm can be performed within the range of the inherent stiffness of the arm by controlling the applied pressure to the cylinder tube. Further, the deformation of the arm by an external force applied to

the upper stage can be modeled by considering the stiffness of the cylinder tube. These both modeling will be our future work.

4. Master Slave Control System and Control Procedure

In the control engineering field, the master-slave control is one of methods used for controlling a system or process in which one device is known as the master, and the other is known as the slave. Once the master-slave relationship is established, the direction of control is always from the master to the slave. The master-slave control which is proposed by this paper is necessary when a physical therapist wants to administer rehabilitation treatment to a patient. The therapist programs the master arm to execute desired movements while the patient repeats the movements with the slave arm. The previous study had also proposed the master-slave control system, (Aliff, et al., 2012). However, the robot arm cannot move naturally and precisely. These problems cause that the robot arm has not been used yet as a rehabilitation robot. Moreover, the movement of the robot arm is not smooth causing concern for the patient safety if used for therapy. Figure 6 is a photograph of a master slave control system. The device on the left is the slave arm and on the right is the master arm.

Fig. 6 Master slave control system

The master arm consists of an accelerometer that is set on the top of a flexible tube to give the reference attitude. The attitude of the upper round stage is detected with the accelerometer atop in the upper round stage. The value for the bending direction angle α and the bending angle β are given by the following equations which are using the output voltage from the accelerometer.

$$\alpha = \cos^{-1} \frac{V_x}{\sqrt{V_x^2 + V_y^2}} \quad (16.1)$$

When V_y is negative, α is calculated by Eq. (16.2).

$$\alpha = 2\pi - \cos^{-1} \frac{V_x}{\sqrt{V_x^2 + V_y^2}} \quad (16.2)$$

$$\beta = \cos^{-1} \left(\frac{V_z}{V_{zmax}} \right) \quad (17)$$

Where, V_x , V_y , and V_z are the output voltages from the accelerometer. The voltages V_x and V_y correspond to the angle from the horizontal plane and V_z corresponds to the angle from the vertical plane. The V_{zmax} means the difference of V_z between the values in horizontal and vertical planes. Figure 7 shows the schematic diagram of the master slave control

system. The slave arm consists of the tested robot arm, an accelerometer, the embedded controller (Renesas Co. Ltd., SH7125) and six quasi-servo valves.

Fig. 7 Schematic diagram of master slave control system

In the control system as shown in Fig. 7, the master-slave control is carried out as follows, (Aliff, et al., 2012). The microcomputer gets the output voltage from the master and slave accelerometers through the A/D converter. Bending direction angle α , bending angle β , and distance L between upper and lower round stage are calculated with the SH 7125 microcomputer by using the analytical model. In this system, six PWM control valves are controlled by three PWM control ports. This means that the exhaust and supply ports of a cylinder are controlled by the same duty ratio. Finally, by using the quasi-servo valve (PWM control valve) and PID control scheme based on the difference of the length of the cylinder, the bending motion of the robot is controlled. The values of angles and displacements during the operation were output through the added D/A converter to the microcomputer, and were recorded with the data recorder (GRAPHTEC, GL200). For the master-slave control method, by using the tested quasi-servo valve, the following typical PID control scheme was applied and embedded into the SH7125 microcomputer.

$$u_i = K_p e_i + K_I \int e_i dt + K_D \frac{de_i}{dt} \quad (i=1,2,3) \quad (18)$$

$$e_i = L_{im} - L_{is} \quad (i=1,2,3) \quad (19)$$

Where, u_i is the control input, e_i is the deviation of each cylinder length and subscript i is the cylinder number. K_p ($=8.2[\%/mm]$), K_I ($=0.0049[\%/mm]$) and K_D ($=38.5 [\%/mm]$) are the proportional gain, the integral gain and the differential gain, respectively. These control parameters are adjusted based on the ultimate sensitivity method. Using the lower duty ratio as a control input to the PWM valve, there exists a dead zone for output flow rate of the valve. Therefore, the input duty ratio of the PWM valve is always added by 22.5% to the absolute value of the control input which is calculated by Eq. (18). Furthermore, the state of the switching valve is decided by the sign (positive or negative) of the control input. Since this control method is embedded into the microcomputer, we can use the valve like a typical servo valve without complex operations. During the experiment, the master arm is operated by a human hand to be bent, extended and contracted. The control sampling period is 2.3ms, and the PWM period of the quasi-servo valve is 10ms.

5. Control Results and Discussions

5.1 Position Control of Single Flexible Pneumatic Cylinder

Figure 8 shows the calculated and experimental results of the position control of a single flexible pneumatic cylinder for sinusoidal desired position that an amplitude of 30 mm was used in various input frequency; 0.1, 0.25 and 0.5 Hz.

Fig. 8 Calculated results of position control

In the figure above, solid red lines, the broken blue lines and blue circles show the desired position, the calculated and the measured position of the cylinder, respectively. In the calculation, Matlab Simulink with Runge-Kutta method was used. As a condition of the calculation, the sampling period of 2.3 ms of the embedded controller with 10 bit A/D converter and the PWM period of 10 ms for the quasi-servo valve were used. As a control method, the following proportional control scheme was used.

$$u = K_p |e| + 22.5 \quad (20)$$

where u and e mean the duty ratio for the PWM valve in the quasi-servo valve and the error of the cylinder displacement, respectively. The on/off valve, which is switching valve in the quasi-servo valve, is changed based on positive and negative value e . If $e > 0$, the valve turns on, which is the supply mode. Otherwise, it is the exhaust mode that the valve turns off. The value of 22.5 % in Eq. (20) indicates the additional duty ratio to compensate the dead zone of the PWM control valve, (Zhao, et al., 2010). In the calculation, a proportional gain K_p of 4.1 %/mm was used. This value could be obtained from the proportional gain in the case that the calculated integrated error of the cylinder displacement in the tracking position control becomes smallest. The system parameters used in the calculation are

shown in Table 1 and Table 2. Table 1 shows the system parameters of the quasi-servo valve, (Zhao, et al., 2010). Table 2 shows the system parameters of the flexible pneumatic cylinder and robot arm which are identified in this study. From Fig.8, it can be seen that the controlled position of the cylinder can trace the desired position with stepwise change around desired position for lower input frequency from 0.1 to 0.25 Hz. In order to confirm the validity of the proposed model and the identified system parameters, the comparison between the experimental and calculated results was executed.

Table 1 System parameters of the quasi-servo valve, (Zhao, et al., 2010).

A_{s0}	0.2×10^{-6}	m^2
A_{a0}	0.3×10^{-6}	m^2
A_{p0}	0.2×10^{-6}	m^2
C_v	0.6	Ns/m
K_c	0.8	N/A
K_v	376.2	N/m
L_v	0.552×10^{-3}	H
M	0.809×10^{-3}	kg
R_v	42.2	Ω
x_{min}	0.27×10^{-3}	m
x_{max}	0.54×10^{-3}	m

Table 2 System parameters of the flexible cylinder and robot arm.

A_F	$\pi/4 \times 0.008^2 = 5.03 \times 10^{-5}$	m^2
V_{FR0}	$A_F \times (0.175 + 0.005) = 9.054 \times 10^{-6}$	m^2
V_{FL0}	$= V_{FR0}$	m^2
C_F	55	Ns/m
M_F	$0.121 = (\text{round stage and tube } 0.336 + \text{potentiometer rod } 0.027) / 3$	kg
F_s	6	N
F_c	3	N
ε_v	0.001	m/s

Figure 9 shows the experimental setup for the position control system using the flexible pneumatic cylinder. The system consists of a flexible pneumatic cylinder with a stroke of 350 mm, a potentiometer and an embedded controller (Renesas Co. Ltd. SH7125). The blue circles in Fig. 8 show the experimental results using the setup as shown in Fig.9. The same experimental conditions and control scheme as the calculation were used. When comparing the two results, it can be seen that the calculated results agree well with the experimental results such as the step-wise change around the desired position and the delay of the transient response of the displacement for lower input frequency. This means that the proposed model with nonlinear frictional force model and the identified system parameters are valid.

Fig. 9 Experimental setup for position control system of the cylinder

5.2 Master Slave Control of Robot Arm

In order to confirm the effectiveness of the proposed model and identified system parameters, it is necessary to compare the calculated result of the analytical model for the overall robot arm with the experimental result. In the simulation, the value of the frictional force is set with the identified values where the static friction is 6 N and the Coulomb force is 3 N, and the other system parameters are shown in Table 2. Figure 10 shows the comparison of the calculated results with experimental values for the cylinder length L_1 , L_2 , L_3 and the bending direction angle α . In these figures, the blue lines are the desired target values which are calculated by Eqs.(8) to (11) and Eqs.(16) and (17) based on the accelerometer's output voltages of the master arm, the red lines are the calculated results using the proposed overall analytical model of the robot arm and the blue circles are the experimental values which are executed by using SH7125 microcontroller based on the accelerometer's output voltages. In both experiment and simulation, the values of β and L are kept constant: $\beta = 73$ deg. and $L = 0.131$ m. From the comparison between the calculated values and the

experimental values, it can be seen that the calculated results agree well with the experimental results. As a result, we can conclude that the analytical models for the overall robot arm were obtained and the validity of the proposed models was confirmed.

Fig. 10 Comparison of calculated result with experimental value for the cylinder length (a) L_1 , (b) L_2 , (c) L_3 and (d) the bending direction angle α

6. Conclusions

This study focusing on the control and analysis of the robot arm using flexible pneumatic cylinder can be summarized as follows:

- 1) The analytical model of a single flexible pneumatic cylinder was proposed and the system parameters of the cylinder were identified. The calculated result of the tracking control was compared with the experimental result. As a result, the effectiveness of the proposed models and system parameters were confirmed.
- 2) In order to design and simulate the master-slave control system of a robot arm, an analytical model of the whole robot arm and control system was proposed. The model consists of the slave arm, six quasi-servo valves, an embedded controller and a master arm. A model of the slave arm is composed of the models of three flexible pneumatic cylinders with slide stage.
- 3) A simulation of the master-slave attitude control was carried out and the calculated result was compared with the experimental result. The results show that the proposed analytical model can predict the behavior of the robot arm and the master-slave control.

We are going to carry out the optimal design of the robot arm by using the proposed analytical model. And, we will apply the tested robot arm to a rehabilitation device for a human wrist.

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