Development of Rodless Type Flexible Pneumatic Cylinder and Its Application

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Abstract:
In Japanese society, an important problem of providing nursing care for the elderly has occurred. As a result, it is necessary to develop systems to aid in nursing care. The actuators required for such a system need to be flexible so as not to injure the body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be attached to the human body. We propose new types of flexible pneumatic actuators that can be used even if the actuator is deformed by external forces. In this study, we tested rodless type flexible pneumatic cylinders and investigated characteristics of the cylinders. We also applied the tested cylinders to a rotary actuator for a master-slave robot arm.

Keywords: Flexible Pneumatic Cylinder, Flexible Actuator, Flexible Rotary Actuator, Soft Actuator, Master-Slave Robot Arm

Introduction

Virtual reality has been flourishing as an interactive information technology. Recently, virtual reality systems that feed back to human senses have only been realized as visual and acoustic feedback. However, they are not enough to realize the force feedback system for hands, arms, legs and so on. Furthermore, due to the ageing in Japanese society and the decreasing birth rate, an important problem of providing nursing care for the elderly has occurred. As a result, it is necessary to develop systems to aid in nursing care[1]. The actuators required for such a system need to be flexible so as not to injure the body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be attached to the human body. We propose new types of flexible pneumatic actuators that can be used even if the actuator is deformed by external forces[2][3]. In this study, we tested rodless type flexible pneumatic cylinders and investigated characteristics of the cylinders. We also applied the tested cylinders as a rotary actuator for a master-slave robot arm.

Rodless Type Flexible Pneumatic Cylinder

Construction and operating principle
Figure 1 shows the construction of a rodless type flexible pneumatic cylinder. It consists of a flexible tube as a cylinder and gasket, two steel balls as a cylinder head and a slide stage that can slide along the outside of the tube. The slide stage has two rollers set on the inner bore of the stage in order to press and deform the tube toward the center of the tube. The operating principle of the cylinder is as follows. When a supply pressure is applied to one side of the cylinder, the inner steel balls are pushed. At the same time, they push rollers and move the slide stage while they deformed the tube. The two balls are not connected to each other, that is, each ball can move independently. Therefore, the balls can move along the curved tube in the same manner as along a straight tube.
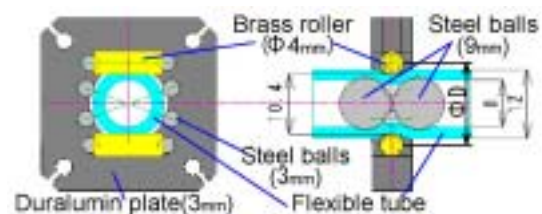

Fig. 1: *Rodless type flexible pneumatic cylinder*

Estimation of holding and actuation
In order to estimate to maintain unit configuration the inner balls and slide stage and actuation when the pressure of 500 kPa is applied to the cylinder. We call it "holding" for short. We investigated them using the parameters such as the center distance D between two rollers and the diameter of inner steel ball. As a method of estimation of holding, we judge the possibility of holding them when the pressure of 500 kPa is applied to the cylinder. And we also judge the possibility of holding when we give external force to the slide stage under the condition when the supplied pressure is 500 kPa. Figure 2 shows the relation between the distance D and the minimum pressure for actuation of the tested cylinder. In Fig.2, each symbol ● and ▲ shows the experimental results using the inner steel balls with a diameter of 9.0 mm

and 9.5 mm, respectively. Vertical lines show the scatter in measured values. From Fig.2 and the results of estimation of holding[3], we can see that the cylinder by using distance D of 14.6 mm and inner steel ball with a diameter of 9.0 mm required the lowest driving pressure of 130 kPa.
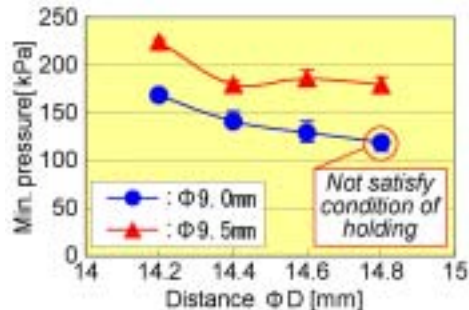

Fig. 2: *Minimum pressure for actuation*

Master-Slave Robot Arm Using Tested Cylinder

Construction and characteristics
As an application using the tested cylinder, Fig.3 shows the construction of a tested slave robot arm using a flexible rotary actuator that consists of two tested cylinders. Both ends of each cylinder are connected with one connector which has two inlets. The slide stages and connecters are fixed on the two links of the robot arm that have a rotary joint which is made of a potentiometer. The actuator has advantages that the actuator can rotate the robot arm joint even if a little deflection between both rotating axis of the robot arm and the actuator exists. Because the tested pneumatic cylinders have flexible characteristics that can be enough to rotate the actuator eccentrically while they make the cylinder tube deformed. Two on/off valves are set on the joint to drive the actuator clockwise or counterclockwise.
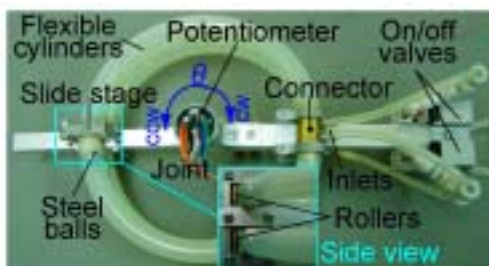

Fig. 3: *Construction of tested slave robot arm*

The tested robot arm is very lightweight. The whole mass of the robot arm which includes the weight of two valves, the rotary actuator, joint and links is about 0.25 kg. The rotation range of the arm is relatively large, that is about 300 deg.

Figure 4 shows the relation between rotating angle and generated torque of the tested flexible pneumatic rotary actuator when supply pressure of 500 kPa applied to one side of the cylinders. The upper or lower figure shows the characteristics of generated torque toward counterclockwise (ccw) or clockwise (cw) directions, respectively. In Fig.4, each symbol ●, ▲ and ■ shows experimental results using an inscribed circle diameter of 60, 100 and 200 mm, respectively. From Fig.4, we can see that generated torque increased according to the inscribed circle diameter of the cylinder. However, it can be seen that generated torque in the point of 180 deg. of robot arm angle becomes the lowest in every case. This is caused by the stiffness of the actuator becoming least under condition of greatest extension of the robot arm (180 deg.) because of the flexibility of the cylinder. It can be seen that the generated torque using the rotary actuator with an inscribed circle diameter of 100 mm is relatively stable for every rotating angle compared with other cases. We think that the diameter of 100 mm is suitable to apply to the rotary actuator.
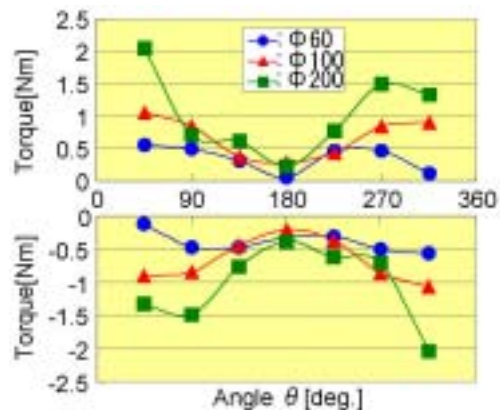

Fig. 4: *Generated torque of tested actuator*

Master-slave control system
Figure 5 shows a tested control system of the master-salve robot arm. The system consists of master and slave types of 2-link robot arm and two on/off control valves and a microcomputer (Hitachi Co. Ltd. H8/3664) as a controller. The control of the arm is as follows. First, the microcomputer detects the joint angles of the master and slave robot arm through potentiometers and a 10 bit A/D converter in the microcomputer. The microcomputer calculates the rotating direction of the rotary actuator based on the deviation from desired angle. Then, the actuator of the slave robot arm is driven toward the desired direction by using on/off valves. If the deviation from desired angle is within ± 2.5 deg. , both valves are turned off. In other cases, one side of the actuator is applied by supply pressure of

500 kPa. By using this control method, the slave arm can trace the motion of the master arm.
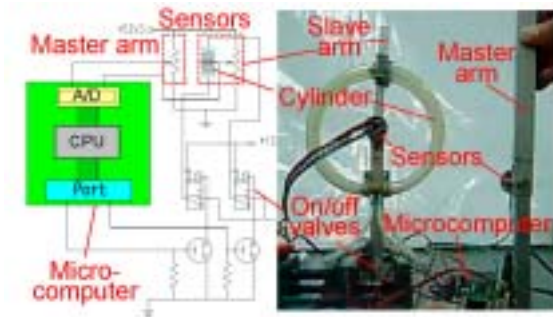

Fig. 5: *Construction of master-slave robot arm*

Control performance of follow up control

Experimental result using On/off control

Figure 6 (a) and (b) show the transient responses of the robot arm joint angle for stepwise and periodical input, respectively. From Fig. 6(a), we can see that a joint angle of the slave arm can reach the desired angle within 0.4 s for a stepwise angular change of about 180 deg.. It can be seen that the steady state error of the response is about –1.9 deg.. The value shows a relatively good control performance compared to a simple control method such as an on/off control using a pneumatic actuator. In the case of tracing the periodic motion as shown in Fig. 6(b), we can see that the slave arm can trace the motion of the master arm with the period of about 2 s exactly, even if the actuator is driven by a small sized on/off valve whose weight is about 15 g. We think that it is possible to improve the dynamic characteristics of the system by using large sized on/off valves with larger flow rate.
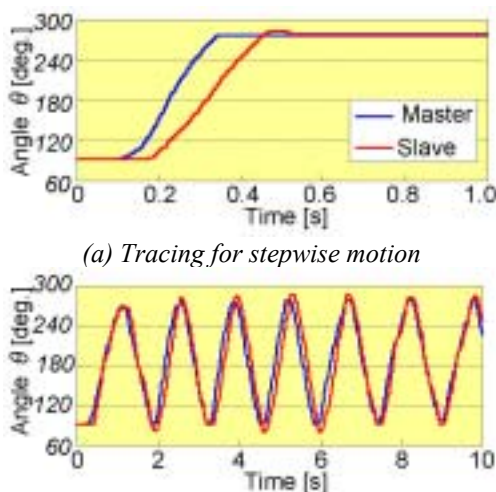
(a) Tracing for stepwise motion

(b) Tracing for periodical motion
Fig. 6: *Transient response of joint angle*

Improvement of control performance

Figure 7(a) shows the transient response of robot arm joint angle for desired angle of 180 deg.. The tested robot arm has the disadvantage that the stiffness of the actuator becomes least under condition of greatest extension of the robot arm (180 deg.) as shown in Fig.4(a). It gives rise to the vibration around the desired angle because of lower stiffness and the time delay of the on/off valves. Therefore, we applied a preview control method to the system. Figure 7(b) shows the experimental result using the preview control method based on error and error speed. The control scheme is expressed in the following equations.

$$u_{(t)} = (1+k)e_{(t)} - ke_{(t-1)} \qquad (1)$$

$$V_R : On, \quad V_L : Off \quad \left(u_{(t)} > 1.76\,\text{deg.}\right) \qquad (2.a)$$

$$V_R : Off, \quad V_L : Off \quad \left(\left|u_{(t)}\right| \leq 1.76\,\text{deg.}\right) \qquad (2.b)$$

$$V_R : Off, \quad V_L : On \quad \left(u_{(t)} < -1.76\,\text{deg.}\right) \qquad (2.c)$$

where $e_{(t)}$ shows the error and k means the gain corresponding to preview time. V_R and V_L show the state of right and left side on/off valves, respectively. In the experiment, we used the value of 50 as the gain k. From Fig.7(b), we can see that the vibration around 180 deg. can be reduced. The steady state error is improved to about –0.38 deg..
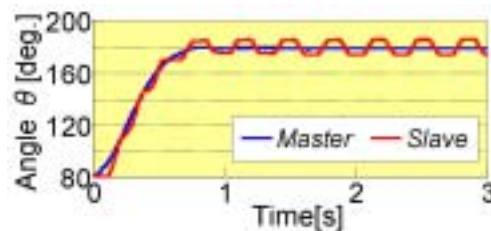
(a) On/off control
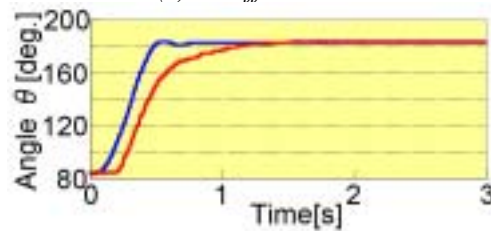
(b) Preview on/off control
Fig. 7: *Transient response of joint angle for desired angle of 180 deg.*

4-Link Master Slave Robot Arm

Photo.1 shows the construction and view of movement of a 4-link master slave robot arm. The slave arm consists of 4 links, 3 joints made of

potentiometers, 3 tested rotary actuators with an inscribed circle diameter of 100 mm and a small sized pneumatic robot hand. The tested arm is very lightweight; the whole weight of the slave arm including the mass of 7 on/off valves and 3 potentiometers is about 0.86 kg. The length of the arm is 0.78m. The arm is controlled by the preview on/off control method mentioned above. As an estimation of its control performance, we applied it to bending and stretching actions as shown in Photo.1.
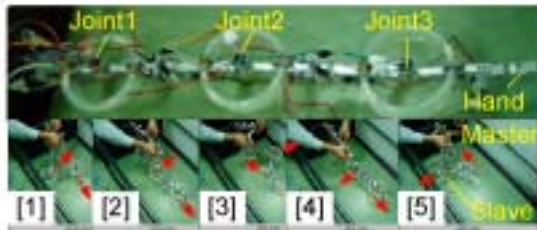

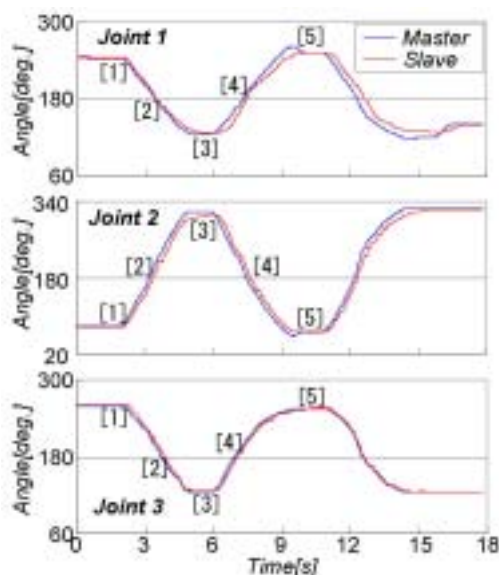***Photo. 1:*** *Construction and view of movement of 4-link master slave robot arm*

Fig. 8: *Transient response of each joint angle*

Figure 8 shows the transient response of each joint of the tested robot arm. In Fig.8, each number shows the time schedule for the movement as shown in Photo.1. We can see that each joint can almost trace the movement of the master arm. In the results of joint 1 and 2, a little tracking error appears. We think that it was caused by disturbances such as an inertial force change, it is possible to improve control performance by using control methods considered with inertial force change. However, we can see that the results show a relatively good control performance for complicated motions by using simple control methods. We can expect that

the tested cylinder is useful to apply in various driving systems with advantages of flexibility, lightweight and easier positioning compared with the case using an ordinary pneumatic cylinder.

Conclusions

This study aiming at the development of a flexible and lightweight actuator which can be safe enough to the human body can be summarize as follows:

1) We tested rodless type flexible pneumatic cylinders that consist of a flexible tube as a cylinder and rod. And we investigated the condition of actuation for various design parameters. As a result, we could find the tested actuator required a minimum driving pressure of 130 kPa.

2) We proposed and tested the flexible pneumatic rotary actuator which consists of two rodless type flexible pneumatic cylinders. As a result of investigation of generated torque characteristics, we confirmed that the actuator with an inscribed circle diameter of 100 mm is most suitable as a rotary actuator.

3) As an application using rodless flexible pneumatic cylinders, we tested a master slave robot arm using the tested rotary actuator. The results show a relatively good control performance in the case using a simple control method such as an on/off control using a pneumatic actuator.

We can expect that the tested cylinder is useful to apply in various driving systems with advantages of flexibility, lightweight and easier positioning compared with the case using an ordinary pneumatic cylinder.

Acknowledgments

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