Development and Control of Flexible Spherical Actuator for Portable Rehabilitation Device

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***Abstract*—This study aims at developing a potable rehabilitation device which can be safe to use during holding it. In our previous study, a novel flexible pneumatic cylinder that can be used even if it is deformed by external force has been developed. In this paper, a portable rehabilitation device using the flexible spherical actuator that consists of two ring-shaped flexible pneumatic cylinders is proposed and tested. The low-cost control system using four small-sized quasi-servo valves and an embedded controller is also developed. The spherical actuator is also improved so as to apply to the portable rehabilitation device. In addition, the attitude measuring system for attitude control of the device using a tiny embedded controller and two accelerometers is constructed and tested. The attitude control of the device using the measuring system is executed. As a result, the portable rehabilitation device that it is possible to give the rehabilitation motions to patients with attitude control can be realized.**

***Index Terms*—portable rehabilitation device, flexible pneumatic cylinder, flexible spherical actuator, embedded controller, low cost**

I. Introduction

In an aging society, it is required to develop a system to aid in nursing care [1] [2] and to support the activities of daily life for the elderly and the disabled [3]. The actuators used in such a system need to be flexible so as not to injure the human body [4]. The purpose of this study is to develop a portable rehabilitation device that can be safe enough to use it while handling it with hands. In our previous study, a novel flexible pneumatic cylinder that can be used even if the cylinder is deformed by external forces has been proposed and tested [5]. We also developed a flexible robot arm and a spherical actuator using the flexible pneumatic cylinders, which can be used on a table as a rehabilitation device for human wrist and arm [6] [7] [8]. In this paper, a portable rehabilitation device using the flexible spherical actuator that consists of two flexible pneumatic cylinders is proposed and tested. The flexible spherical actuator can create larger bending motion along the spherical surface. In order to apply the spherical actuator to the portable rehabilitation device, it is necessary to improve the spherical actuator to obtain larger moving area and higher generated torque. In addition, the attitude measuring system at the handling points is needed. Therefore, an inexpensive measuring system using an embedded controller and accelerometers is proposed and tested. An attitude control system of the portable rehabilitation device using an embedded controller and quasi-servo valves composed of inexpensive on/off control valves is also constructed and several kinds of attitude control are executed.

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II. Flexible Pneumatic Cylinder and Spherical Actuator

A. Flexible Pneumatic Cylinder

Fig. 1 shows the construction of a rod-less type flexible pneumatic cylinder developed by us [5]. The cylinder consists of a flexible tube as a cylinder and gasket, one steel ball as a cylinder head and a slide stage that can move along the outside of the cylinder tube. The steel ball in the tube is pinched by two pairs of brass rollers from both sides of the ball. The operating principle of the cylinder is as follows. When the supply pressure is applied to one side of the cylinder, the inner steel ball is pushed. At the same time, the steel ball pushes the brass rollers and then the slide stage moves toward opposite side of the pressurized while it deforms the tube.

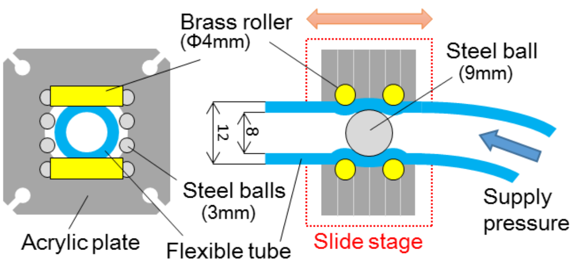

Figure 1. Construction of the flexible cylinder.

B. Previous Flexible Spherical Actuator

The appearance of the previous spherical actuator [7] is shown in Fig. 2. The spherical actuator consists of two ring-shaped flexible pneumatic cylinders which are intersected at right angle and are fixed on the base. Each slide stage is set on the different acrylic plate of the base in order to reduce the gap at the cross position of tubes. This gap is 12 mm. Each cylinder is also held by an additional slider plate set on the opposite acrylic plate of the base that has a distance of 43 mm from the sliding stage. The diameter of each ring-shaped cylinder is 160

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mm. The size of the tested actuator is 160 mm in width and 170 mm in height. The total mass of the actuator is 300 g.

The fundamental characteristics were investigated. Fig. 3 shows the relation between the supplied pressure and the generated torque of the spherical actuator. The torque is calculated from the measured generated force and radius of the actuator. The torque of x and y direction were calculated based on the distance of 85 mm and 80 mm from the center of each ring-shaped cylinder to the fixed position of the force sensor, respectively. From Fig. 3, it is found that the maximum generated torque in the x-direction is 0.45 Nm and the y-direction is 0.47 Nm. The actuator has a dead zone of the generated torque for the lower supplied pressure. This corresponds to a minimum driving pressure of 120kPa of the flexible pneumatic cylinder caused by a friction of the cylinder.

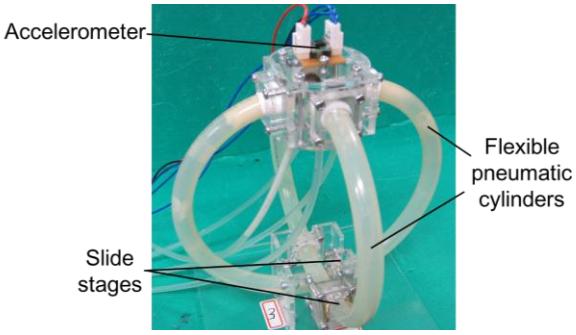


Figure 2. Previous flexible spherical actuator.

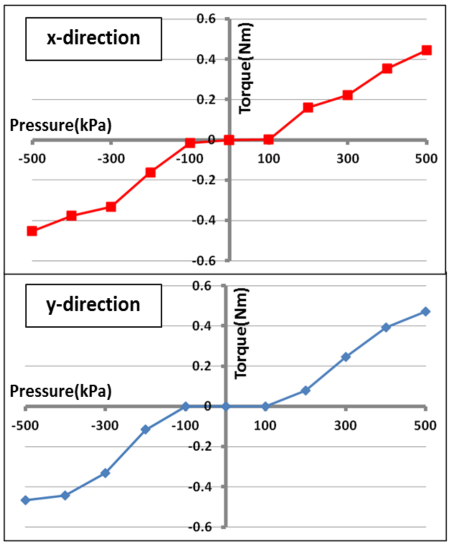


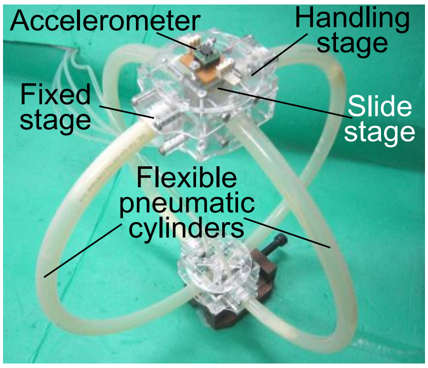
Figure 3. Generated torque of tested actuator.

III. Portable Rehabilitation Device

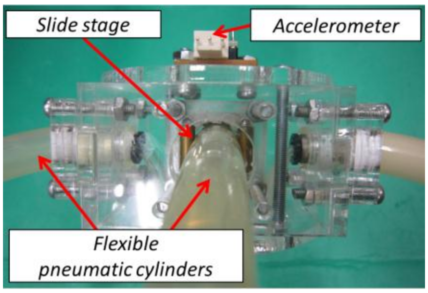
A. Construction

Fig. 4 (a) shows the appearance of the tested portable rehabilitation device using the spherical actuator. The device is developed as a rehabilitation device for shoulders and arms. It is imaged that patients will have both handling stages, which are top and bottom stages in Fig. 4, by their both hands in the rehabilitation. When we apply the previous spherical actuator to the rehabilitation device, it is necessary to increase the moving area and the generated torque of the actuator. Therefore, the diameter of the ring-shaped flexible pneumatic cylinder is changed from 160 mm to 260 mm. Unlike the previous spherical actuator in Fig. 2, two slide stages of each flexible cylinder are not connected with one side base, that is, each slide stage of the flexible cylinder is fixed on each handling stage as shown in Fig. 4 (b). The size of the actuator is 260 mm in width and 270 mm in height. The total mass of the device is 310 g. In addition, to measure the attitude angle of each handling stage, two accelerometers are used as angular sensors.

Fig. 5 shows the transient view of the movement of the device. In the experiment, the sequential on/off operation of the control valve every 0.8 seconds was done. The supply pressure of 450 kPa is applied. From Fig. 5, it can be seen that the device can create the different attitudes easily. We also observed that the device can work smoothly while the human holds it by both hands.



(a) Appearance of the device



(b) Detailed photo of the handling stage

Figure 4. Portable rehabilitation device.

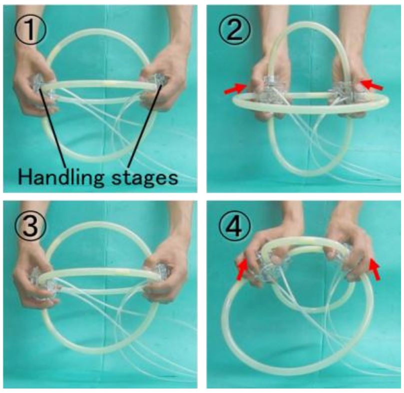


Figure 5. Transient view of the movement of the rehabilitation device.

B. Master-Slave Attitude Control System

In order to control the attitude of the device, it is necessary to measure the angular change of both stages at holding points of the device. The angular change θ, ψ and φ defined as shown in Fig. 6 are given by the following equations, respectively [9]. Where, A_{xout}, A_{yout} and A_{zout} are incremental A/D values for x, y and z axis in the accelerometer.

$$\theta = \tan^{-1}\left(\frac{A_{xout}}{\sqrt{A_{yout}{}^2 + A_{zout}{}^2}}\right) \tag{1}$$

$$\psi = \tan^{-1}\left(\frac{A_{yout}}{\sqrt{A_{xout}{}^2 + A_{zout}{}^2}}\right) \tag{2}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{A_{xout}{}^2 + A_{yout}{}^2}}{A_{zout}}\right) \tag{3}$$

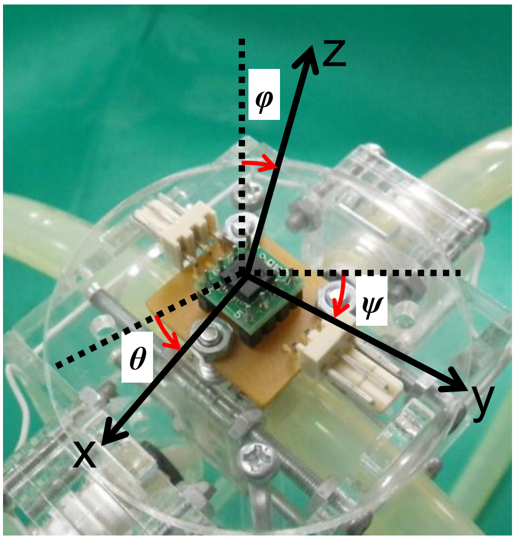


Figure 6. Attitude angle (θ, ψ and φ).

Fig. 7 shows the schematic diagram of the master-slave attitude control system of portable rehabilitation device. The control system consists of the improved spherical actuator with two accelerometers as a slave device, master device with an accelerometer, four quasi-servo valves [10] to operate two flexible pneumatic cylinders and a microcomputer (Renesas Co. Ltd., SH7125) as a controller. The accelerometers were used as angular sensors of the master and slave handling stages. The attitude control of the device is done as follows. The desired angles between both stages are given by the sequential data or master device operated by physical therapist. For measuring the master and slave stage's angles, the microcomputer gets the output voltages from each accelerometer. The angle between both handling stages in the slave could be obtained from the calculated angles of each stage. According to the deviation between the master's and the slave's angle, the quasi-servo valves are driven based on the control scheme, and the flexible pneumatic cylinders are driven. The sampling period of the control is 4 ms. The PWM period of the quasi-servo valve is 10 ms. Both the angular measuring of the devices and the attitude control could be realized by using an embedded controller. Fig. 8 shows the view of the attitude control system. The total mass of the system including the controller and the valves is small, about 0.9kg. We think that it will be possible to unite these components to construct the more portable rehabilitation device as our future work.

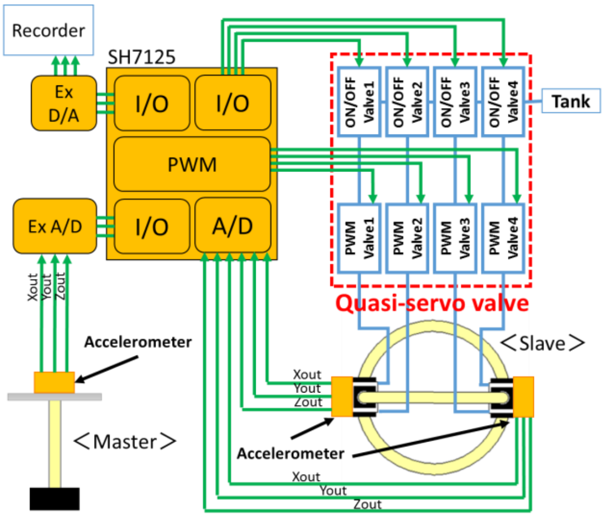


Figure 7. Attitude control system of the device.

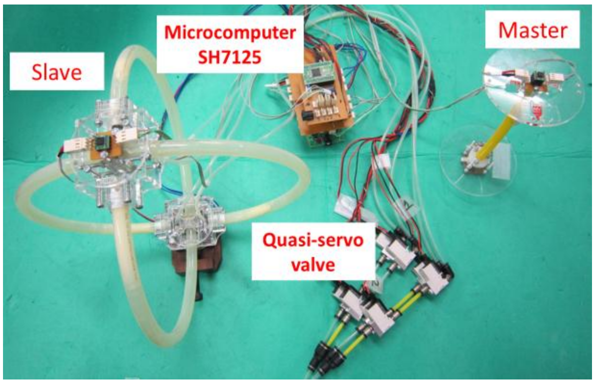


Figure 8. View of the attitude control system.

IV. Control Results

A. Sequential Control

Fig. 9 shows the transient responses of the incremental angles for θ and φ between both stages of the slave device by using (1) to (3). In the experiment, the device was driven by the attitude control system as shown in Fig. 7 so that the angles for x and y directions of the device are changed every 0.8 s. In Fig. 9, the solid line shows the incremental angle of θ, and the broken line shows the incremental angle of φ. From Fig. 9, we can confirm that the attitude angles of both stages in the device can be measured.

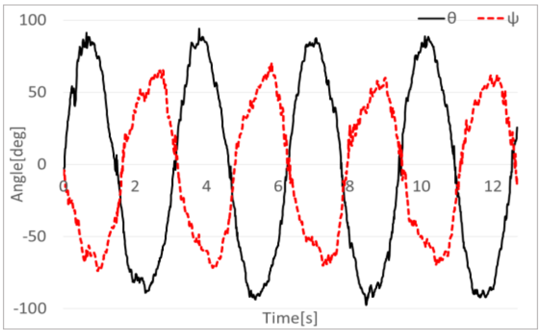


Figure 9. Transient response of stage angle θ and φ.

B. Tracking Control

As an attitude control of the device, we carried out a tracking control using the system as shown in the Fig. 7. In the experiment, the supply pressure of 400 kPa was applied. Simple P control was used as a control scheme. Two kinds of motion of the slave device were tested. One is the cross motion that the x and y directions are independently driven, the other is the circular motion. In the cross motion, the desired angles are given by (4), and (5) and (6) are used in the circular motion as desired angles. θ_r[deg] and ψ_r[deg] are the desired angles of θ and ψ, respectively.

$$\begin{array}{lll} 0s < t \le 4s & \theta_r = 0° & \varphi_r = 0° \\ 4s < t \le 8s & \theta_r = 45° & \varphi_r = 0° \\ 8s < t \le 12s & \theta_r = 0° & \varphi_r = 0° \\ 12s < t \le 16s & \theta_r = -45° & \varphi_r = 0° \\ 16s < t \le 20s & \theta_r = 0° & \varphi_r = 0° \\ 20s < t \le 24s & \theta_r = 0° & \varphi_r = 45° \\ 24s < t \le 28s & \theta_r = 0° & \varphi_r = 0° \\ 28s < t \le 32s & \theta_r = 0° & \varphi_r = -45° \end{array} \tag{4}$$

$$\theta_r = 55\sin(0.67t) \tag{5}$$

$$\varphi_r = 55\sin(0.67t - 1.55) \tag{6}$$

The measured and calculated angles are stored to a data recorder as a voltage change through an external D/A converter as shown in Fig. 7. Fig. 10 shows the experimental setup of the slave device for tracking control. In the experiment, the attitude control was executed in both cases when the hand is put on the stage as a load or not. Fig. 11 and Fig. 12 show the transient responses of the stage angle in the device for cross motion and circular motion, respectively. In Fig. 11 and Fig. 12, broken lines show the desired angles (θ_r and φ_r) and solid lines show the controlled angles (θ and φ) of the slave device, respectively.

From Fig. 11 and Fig. 12, it can be found that there is a little vibration around desired angle. However, it can be said that the device can trace the desired angles. It can be also found that there is a large overshoot in Fig. 11 (b). We think that this is caused by the increase of the inertial force because of the increased mass of stage by the hand put on the stage. In addition, it can be seen that the angular vibration becomes smaller when the hand is put on the stage. This is because the dumping of the handling stage is increased. Compared with the cross motion, in the circular motion a rapid change of the desired angle is not given. Therefore, the influence of the damping characteristics is appeared more remarkably in the controlled result.

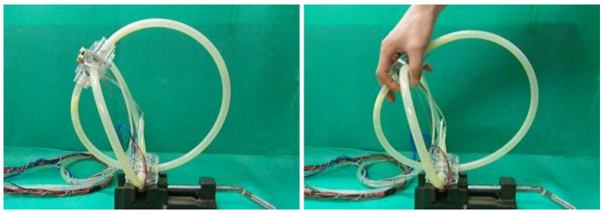
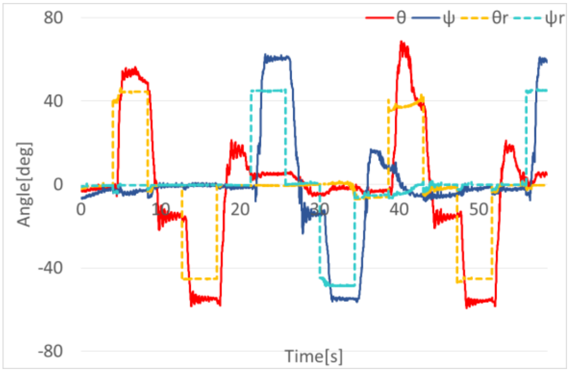
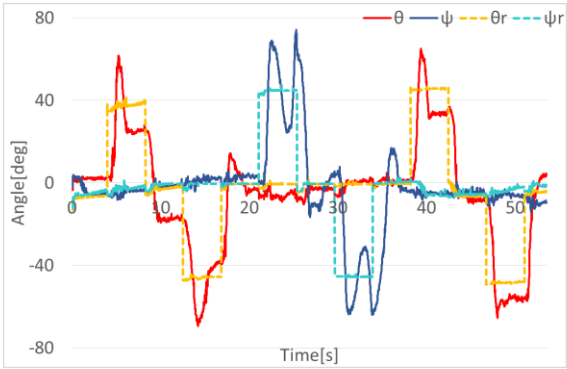


Figure 10. View of the experimental setup for tracking control.

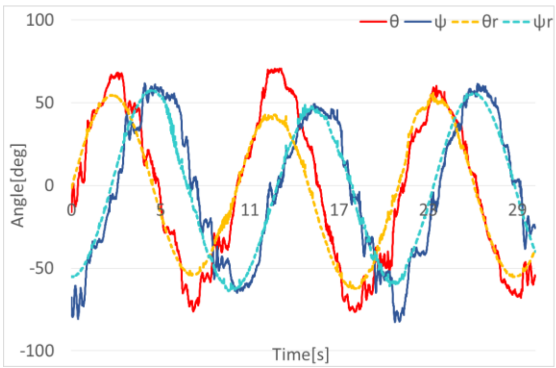


(a) Without hand

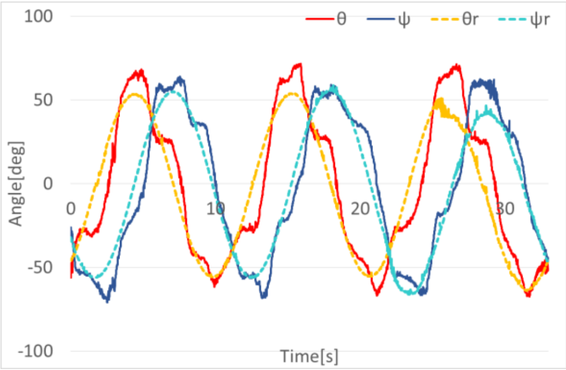


(b) With hand

Figure 11. Transient response of stage angle for cross motion.



(a) Without hand



(b) With hand

Figure 12. Transient response of stage angle for circular motion.

C. Master-Slave Control

We also carried out a master-slave control using the system as shown in the Fig. 7. In the experiment, we gave similar movements to the above tracking control to the master device. The experimental setup and situation are shown in Fig. 13. Fig. 14 and Fig. 15 show the transient responses of the angles of the stage in the device for a cross motion and circular motion, respectively. In both figures, each line shows a same angle in the previous result as shown in Fig. 11 and Fig. 12.

From Fig. 14 and Fig. 15, it can be seen that the controlled results show the similar tendency to the tracking control: the angular vibration in the case when the hand is put on the stage becomes smaller than the case without hand. Compared with Fig. 11 (b), Fig. 14 (b) shows smaller overshoot. This is because the rapid change of the desired angle is not applied by the master device in the master-slave control.

It can be also found that there is a little large error between the master and slave angles. These errors and overshoots will be reduced by using more robust control scheme and adjusting the control parameters.

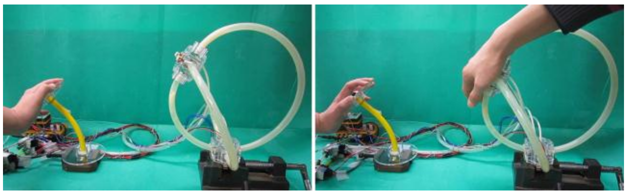
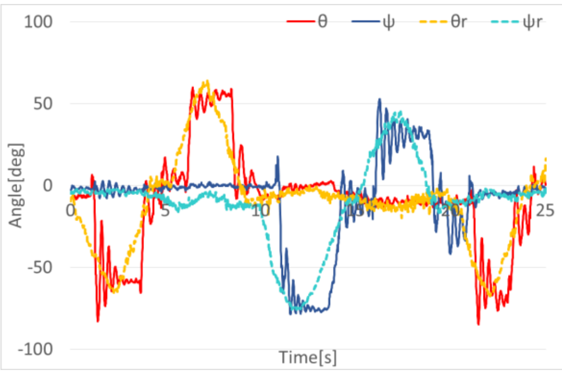
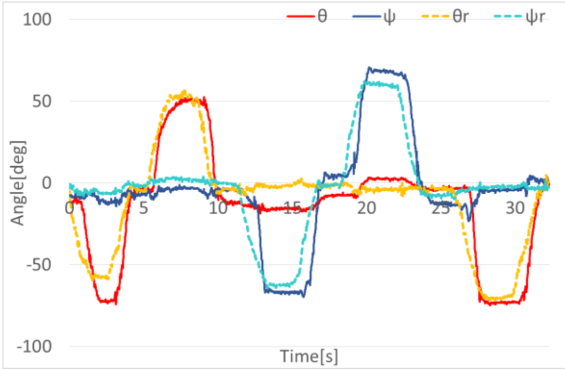


Figure 13. View of the experimental setup for master-slave control.

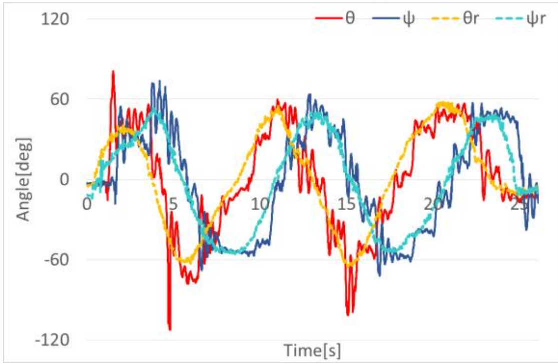


(a) Without hand

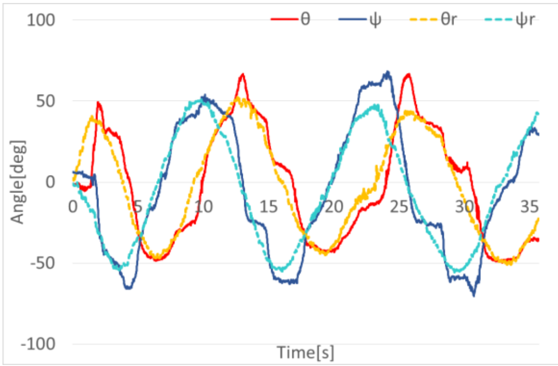


(b) With hand

Figure 14. Transient response of stage angle for circular motion using master-slave control.



(a) Without hand



(b) With hand

Figure 15. Transient response of stage angle for circular motion using master-slave control.

V. CONCLUSIONS

This study that aims to develop the portable rehabilitation device can be summarized as follows.

1) The portable rehabilitation device that was constructed by the improved flexible spherical actuator using two flexible pneumatic cylinders was proposed and tested. The driving test using the device was executed. As a result, we could confirm the validity of the portable device because of its light-weight and flexibility.
2) For measuring the angle between both handling stages in the device, the attitude measuring system was proposed and embedded into the microcomputer. As a

result, we found that the attitude of the device could be measured even if the device was held by hands.

3) The attitude control system using embedded controller was proposed and tested. The tracking control and master-slave control using the tested system were executed. As a result, the device could be controlled by using the tiny embedded controller. We confirmed the possibility of the tested portable device that can give the rehabilitation motions to the patients with attitude control.

As our future work, we aim to improve the control performance by applying the robust control scheme for friction. And we are going to develop a united compact potable device in which the controller and valves are embedded.

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