Flexible Displacement Sensors Using Ultrasonic Sensor for Soft Actuator with Long Stroke

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***Abstract*— Today, a welfare pneumatic equipment to support a nursing care and a self-reliance of the elderly and the disabled is actively researched and developed by many researchers. In the previous study, a portable rehabilitation device with a larger moving area which can give passive exercise for human shoulder was proposed and tested. As an actuator of the device, an extension type flexible actuator was tested. The actuator can extend more than twice of its original length. However, a flexible displacement sensor that can cover the actuator's moving area and be deformed according to the shape of the actuator has not been realized yet. In this study, various flexible displacement sensors using ultrasonic sensors for the actuator are proposed and tested. One is a displacement sensor that ultrasonic sensors are installed into the chamber of the actuator. As a result, it is confirmed that the sensor can not measure the displacement exactly under the condition when a higher supplied pressure is applied to the chamber. Therefore, a displacement sensor using a rubber tube and the ultrasonic sensor is proposed and tested as a sensor without influence of applied pressure. As a result, the sensor can successfully measure the displacement. However, the sensor requires the force to pull the tube. The pulling force causes local deformation of the actuator. Finally, the slide type displacement sensor without pulling force is proposed and tested. As a result, it is confirmed that the tested sensor can measure successfully and exactly.**

***Index Terms*— displacement sensor, ultrasonic sensor, flexible actuator, embedded controller, rehabilitation device**

I. INTRODUCTION

Today, the care and welfare pneumatic equipment using pneumatic soft actuators for a nursing care and a rehabilitation of an elderly and a disabled are actively researched and developed by many researchers[1-3]. K. Yamamoto used a balloon type actuator for power assisting device for nursing care [1]. T. Noritsugu used Mckibben type pneumatic rubber muscles[2] to assist a patient's daily life[3]. H. Kobayashi also used the pneumatic rubber muscle for supporting labor's work[4]. These pneumatic soft actuators have advantages of lightweight and softness based on air compressibility. However, in order to control the pneumatic soft actuator, the actuator also requires a lightweight control valve for each chamber of the actuator and a flexible sensor that can measure the displacement so as not to prevent the motion of the soft actuator. As a lightweight control valve, a small-sized quasi-servo valve that consists of two on/off valves was developed to get precise control performance of the soft actuator[5-7]. As a flexible displacement sensor, in the case using the rubber muscle, the sensor that can measure the displacement indirectly based on the model[8] by measuring the inner diameter of the muscle was proposed and tested[9,10]. In the previous study, a portable rehabilitation device with larger moving area which can give passive exercise for human shoulder was proposed and tested[11]. An extension type flexible actuator was also tested. The length of the actuator becomes more than twice compared with its original length. However, there is no displacement sensor that can measure the larger displacement according to actuator's deformation on the market. In ideal, it is necessary that the flexible sensor does not act on the soft actuator. In this study, various flexible displacement sensors using ultrasonic sensors that can measure larger displacement is proposed and tested. One is a displacement sensor that ultrasonic sensors are installed into the chamber of the extension type actuator. The other is a sensor using the ultrasonic sensors and a rubber tube. A slide type displacement sensor that does not require relatively larger pulling force is also proposed and tested.

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II. BUILT-IN ULTRASONIC DISPLACEMENT SENSOR

A. Extension Type Soft Actuator

Fig. 1 and 2 show a schematic diagram and an overview of an extension type soft actuator developed in our study, respectively. The tested actuator consists of a silicone rubber tube covered with a ruffled fabric sleeve made of nylon string. The rubber tube has an inner diameter of 8 mm, outer diameter of 10 mm and length of 140 mm. The original length of the ruffled fabric sleeve in the stretched condition is 280 mm. The operating principle of the actuator is as follows. When the supplied pressure is applied to the actuator, the inner rubber tube expands toward both radial and longitudinal directions. As the ruffled fabric sleeve can only deform toward longitudinal direction while preventing to expand toward radial direction, the actuator expands longitudinally. From the result of preliminary experiment, it is confirmed that the actuator can extend more than 2.5 times of the original length when the input pressure of 400 kPa is applied.

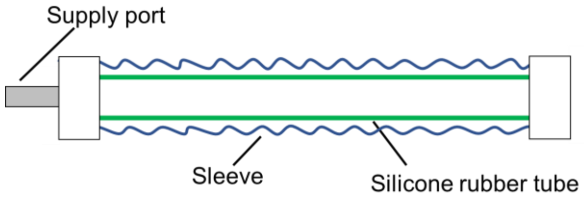

Figure 1. Schematic diagram of the extension type actuator.

Figure 2. Overview of the extension type actuator.

B. Built-in Sensor Using Ultrasonic Sensor

As a measuring method of the displacement of the extension type soft actuator, an ultrasonic sensor is used. The ultrasonic sensor has an advantage that it can measure the displacement without any contacting the object. In the previous study, a flexible displacement sensor using the ultrasonic sensor and a flexible tube with a magnetic slide stage for the flexible robot arm as shown in Fig.3 was proposed and tested. The sensor could successfully measure the displacement of the slide stage between the tube end and the slider even if the tube was bent[12]. However, the tested sensor could not extend or contract such as the extension type actuator. From the view point of compactification of the sensor to apply the actuator, it is better to develop a displacement sensor that can change its length and shape according to the deformation of the actuator.

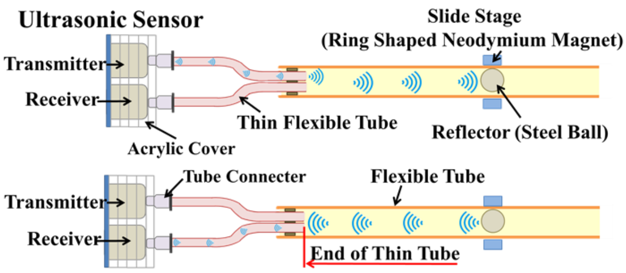

Figure 3. Schematic diagram of the flexible displacement sensor using ultrasonic sensor and tube[12].

Figs. 4 and 5 show a schematic diagram and overview of a measuring system of a built-in displacement sensor using the ultrasonic sensor with an embedded controller for measuring (Renesas electronics Co. Ltd., SH7125). The system consists of a transmitter and a receiver(SPL (Hong Kong) Limited Co. Ltd., UT1612MPR/UR1612MPR) of the ultrasonic sensor(Parallax Inc. Ltd., 28015) that both transmitter and receiver connects with both end of the actuator. Both ultrasonic sensors are covered with acrylic case for sealing. Fig. 6 shows the transient output signal from the ultrasonic sensor. The measuring procedure is as follows. First, the embedded controller of measuring system sends the trigger pulse for 5 micro seconds. Then, the ultrasonic transmitter is driven for 200 micro seconds by the signal with frequency of 40 kHz. The generated ultrasonic wave passes through the rubber tube in the actuator as a transmission tube. When the ultrasonic wave reaches at the ultrasonic receiver, the embedded controller can calculate the distance between the ultrasonic sensor and the slide stage by measuring the time until the receiver detects the ultrasonic wave from the transmitter. It means that the distance can be expressed by the multiplication of the measured time and the speed of sound. By this method, the tested displacement sensor can measure the displacement of slide stage even if the actuator bends.

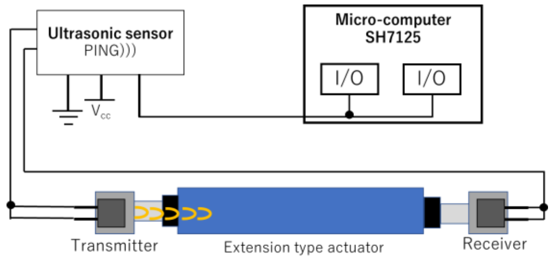

Figure 4. Schematic diagram of the measuring system using built-in displacement sensor.

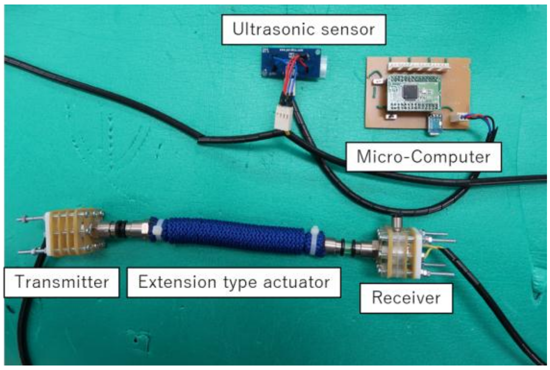

Figure 5. Overview of the measuring system using built-in displacement sensor.

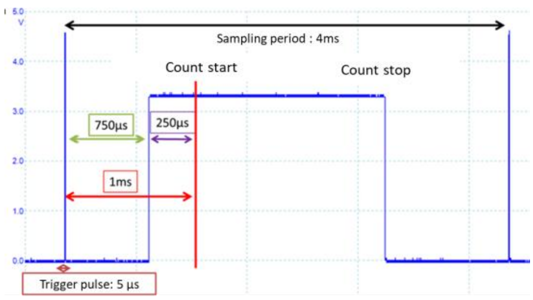

Figure 6. Transient response of output signal from the ultrasonic sensor.

C. Experimental Result and Discussion

Fig. 7 shows the relation between the displacement of actuator and the output counting value from the embedded controller through the ultrasonic sensor. In the experiment, the actuator is pressurized from 0 to 300 kPa and 300 to 0 kPa by using a pressure regulator (Koganei Co. Ltd., PR100). The displacement of the actuator is measured by the potentiometer (MIDORI PRECISIONS Co. Ltd., LP-150FJ) connected with the actuator. From the results, it can be seen that output counting value when the supplied pressure becomes higher has much noise. This deviation from the true value becomes larger in the case using supplied pressure of more than about 100 kPa. In order to investigate the error factor, the extending experiment of the actuator under the condition when the chamber of the actuator is not pressurized was carried out. Fig. 7 shows the relation between the displacement of the actuator and the output counting value from the sensor mentioned above. Compared with the result as shown in Fig. 7, when the actuator is not pressurized as shown in Fig.8, there is little measuring error of displacement. As a result, it can be concluded that it is difficult to measure the displacement under the condition when the transmitter and receiver of the ultrasonic sensor are affected by the higher pressure. Therefore, it is necessary to consider a novel sensor which can measure the displacement of the actuator without influence of the applied pressure.

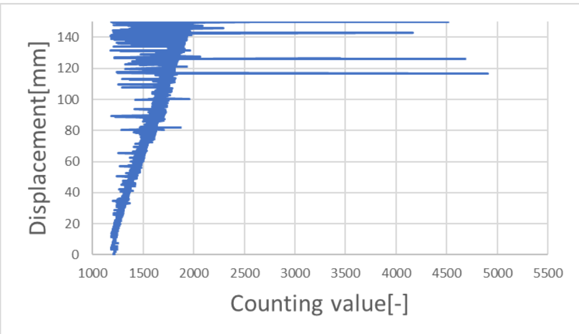

Figure 7. Relation between the displacement of the actuator and the output counting value from the sensor when chamber is pressurized.

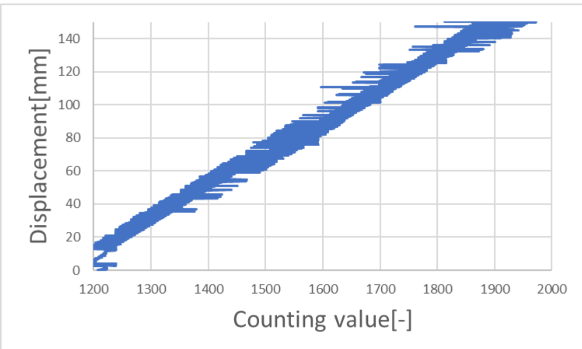

Figure 8. Relation between the displacement of the actuator and the output counting value from the sensor when chamber is not pressurized.

III. Tube Type Displacement Sensor Using Ultrasonic Sensor

As a displacement sensor without pressurized condition, Fig. 9 and 10 show the schematic diagram and overview of a tube type flexible displacement sensor using the ultrasonic sensor. Compared with the previous one as shown in Fig.4, the transmitter and receiver of ultrasonic sensor are only connected with a thin silicone tube through connectors. The silicone rubber tube has an inner diameter of 4 mm, outer diameter of 6 mm and length of 170 mm. The operating principle of the sensor is same as the previous one. By changing the path length of the rubber tube according to the deformation of the actuator, the tested sensor can measure the displacement between the transmitter and receiver.

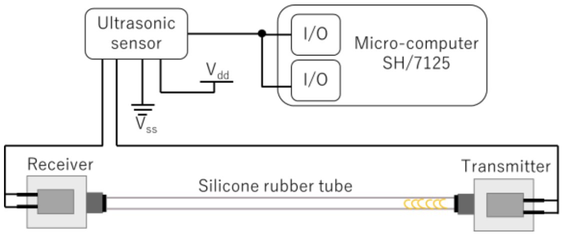

Figure 9. Schematic diagram of the tube type flexible displacement sensor using ultrasonic sensor.

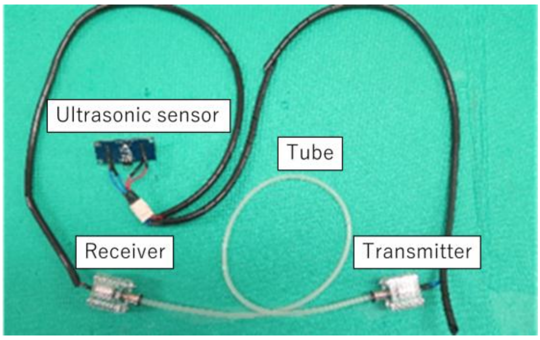

Figure 10. Overview of the tube type flexible displacement sensor using ultrasonic sensor.

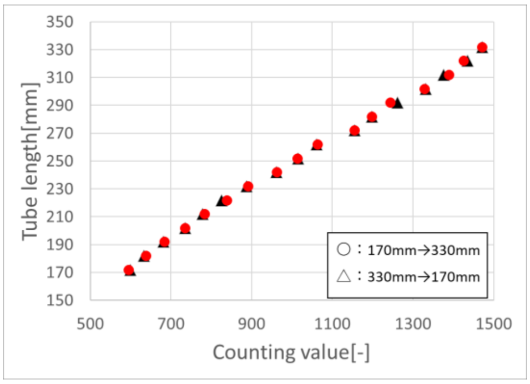

Figure 11. Relation between the tube length and the counting value of the sensor

Fig. 11 shows the relation between the tube length and the counting value of sensor. In the experiment, the rubber tube is stretched from 170 to 330 mm and is released from 330 to 170 mm every 10mm. In Fig.11, the circle and triangle show the results of stretching and releasing the tube, respectively. Each result shows the averaged value of 100 times measurements. From Fig.11, it can be seen that the relation between the stretching tube length and the counting value of the sensor is linear. There is little hysteresis in this relationship. It can be concluded that the measuring method using flexible tube without pressurization is useful to apply to the flexible sensor using the ultrasonic sensor. However, the stretching force of the tube can not be ignored compared with the generated force of the extension type actuator. The generated force is needed more than about 25 N. Therefore, it is better to consider a flexible displacement sensor that can change the tube length with smaller force.

IV. Sliding Tube Type Displacement Sensor Using Ultrasonic Sensor

As a method to change the tube length by using a small pulling or pushing force, a sliding tube mechanism is proposed and tested. Fig. 12 and 13 show the schematic diagram and the overview of a sliding tube type flexible displacement sensor using the ultrasonic sensor. Compared with the previous sensor, the rubber tube is replaced to the sliding mechanism using flexible tubes. The sliding mechanism consists of two thick tubes and a thin tube. The thick tube has an inner diameter of 8 mm and an outer diameter of 12 mm. The thin tube has an inner diameter of 5 mm and an outer diameter of 8 mm. The thin tube is sandwiched by thick tubes from both sides of the thin tube. The one end of each thick tube has an end connector to hold the thin tube. Both end of the thin tube has stopper so as not to come out the thin tube from thick tubes. The length of the sliding tube mechanism can change until twice from the minimum length of the mechanism.

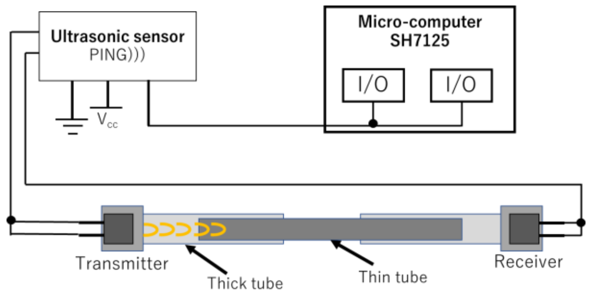

Figure 12. Schematic diagram of the sliding tube type flexible displacement sensor using ultrasonic sensor.

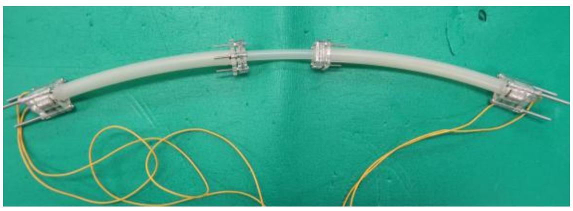

Figure 13. Overview of the tube type flexible displacement sensor using ultrasonic sensor.

Fig.14 shows the relation between the displacement of the sliding tube and the output counting value of the tested sensor. From the result, the generated force of sensor is smaller than the previous tube type sensor. The sensor is driven smoothly without influencing the operation of the actuator. The noise of the output sensor is occurred a little. However it can be seen that the relation between the sensor output and the displacement of the tube is linear. This result means that the tested sensor is useful as a displacement sensor of the flexible extension type actuator. In the future, the displacement of the actuators will be controlled position by using the tested sensor.

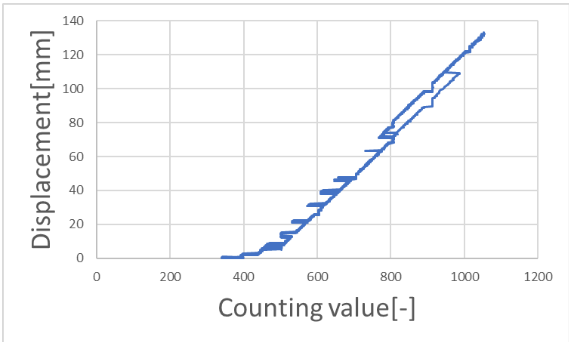

Figure 14. Relation between the displacement of the sliding tube and the output counting value of the sensor.

V. Conclusions

In order to measure the displacement of the extension type flexible actuator with a long stroke, various flexible displacement sensors using ultrasonic sensors that can measure larger displacement were proposed and tested. One is the displacement sensor that ultrasonic sensors are installed into the chamber of the extension type actuator. As a result of measuring test using the sensor, it can be concluded that it is difficult to measure the displacement under the condition when the transmitter and receiver of the ultrasonic sensor are affected by higher pressure of more than 300 kPa. The other is the ultrasonic displacement sensor using a rubber tube as a flexible transmitting tube of ultrasonic waves. From the result of measuring test, it can be seen that the relation between the stretching tube length and the counting value of the sensor is linear. However, the stretching force of the tube of the sensor can not be ignored compared with the generated force of the extension type actuator. Therefore, a slide type displacement sensor that does not require relatively larger pulling force is also proposed and tested. As a result, it can be confirmed that the tested sensor can measure displacement until twice length from the minimum length of the sensor.

As a future work, the tested sensor will be installed into the portable rehabilitation device. Also, the attitude control using sensor feedback will be carried out.

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