Development of Air Supply System for Wearable Robot
-Effectiveness of Hollow Cylindrical-shaped Variable Volume Tank

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Ⅰ. Abstract

Recently declining birthrate and aging population have been causing serious labor shortage. In order to reduce the burden on workers and improve productivity, devices such as wearable power assist robots have been developed. Pneumatic actuators are used in various wearable power assist devices because of their high power-to-weight ratio and flexibility [1]. To drive the actuators, air supply systems are required. The air supply systems are composed of air compressors, tanks, valves and various sensors in most cases. For usability and maneuverability in practical use, the air supply systems are expected to be portable as well as the wearable power assist devices themselves.

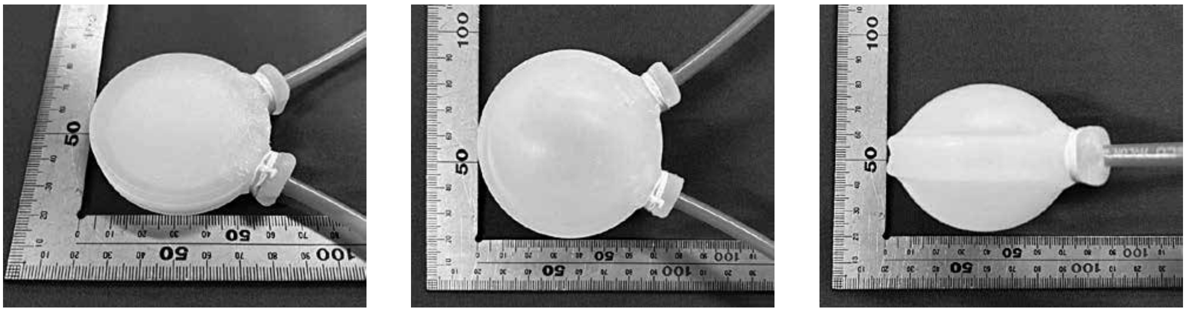
Okui *et al.* proposed a portable power source using chemical reaction of sodium bicarbonate and citric acid [2]. Kitagawa *et al.* suggested an air source by using dry ice [3]. The authors have developed a portable air supply system for retrieving and re-compressing exhausted air using a variable volume tank [4]. Conventional air supply systems have employed constant volume tanks. If a small constant volume tank is used in order to downsize the system, inner pressure of the tank drops significantly when compressed air is supplied to the actuator.

In contrast, the variable volume tank expands when compressed air flows in, and by storing part of the energy of compressed air as elastic energy, it decreases the amount of pressure change. This effect is called pressure relaxation characteristics. However, physical properties of elastomer affect the characteristics of the variable volume tank. Therefore, to increase relaxation-pressure, the tank became thick and heavy. Although a double layer variable volume tank [5] was developed to increase storable pressure without increase in thickness and weight, it became large.

In this study, a hollow cylindrical-shaped variable volume tank is developed as a solution to this issue. This paper describes the effect of decreasing pressure drop based on the pneumatic energy characteristics when compressed air is stored in the developed hollow cylindrical-shaped tank. We also explain the feasibility of achieving the desired energy characteristic at high pressure by multi-layering the tanks to increase outer pressure.

Ⅱ. Hollow cylindrical-shaped variable volume tank

The variable volume tank expands and converts compressed air energy into elastic energy. This effect decreases pressure change. Large internal volume requires high energy to reach the desired pressure for driving the actuator. The spherical-shaped variable volume tank in the previous study has large initial internal volume. If the internal volume is reduced, required energy to increase pressure can be reduced. Also, it contributes to downsizing of the tank as much as reduced internal volume. In order to provide a solution to reducing the internal volume, we have developed the hollow cylindrical-shaped variable volume tank. Figure 1 shows the overview of the hollow cylindrical-shaped variable volume tank. This proposed tank is made of silicone rubber (Shin-Etsu Chemical Co., Ltd.: KE-1316) diluted by adding diluent (Shin-Etsu Chemical Co., Ltd.: RTV-thinner) of 10 percent of the mass of the silicone rubber. The tank has an outer diameter of 60 [mm], a height of 13.2 [mm] , and a thickness of 6 [mm].



(a) Initial state. (b) Pressurized state (Top view). (c) Pressurized state (Side view).

Figure 1. Hollow cylindrical-shaped variable volume tank.

To measure stored energy characteristics of the hollow cylindrical-shaped variable volume tank, an experiment was conducted. Figure 2 shows the experimental setup. First, the three-port solenoid valve (KOGANEI: 100E1- LF) on the inflow side was opened. And the outflow side was closed. In that state, the tank was pressurized with the servo valve (FESTO: MPYE-5-M5-010B) at 0.6 [L/min] until the internal pressure of the tank reaches 65 [kPa]. The inflow energy was measured with the flow sensor (KEYENCE: FD-A1) and pressure sensor (KEYENCE: AP-43A) on the inflow side. Then, the three-port solenoid valve on the outflow side was opened. And the inflow side was closed. The internal air was exhausted at 0.6 [L/min]. The outflow energy was measured with the flow sensor and pressure sensor on the outflow side. Figure 3 shows the measurement results of the energy characteristic of the hollow cylindrical-shaped variable volume tank. For comparison, Figure 4 shows the energy characteristics of the constant volume tanks, of which volume are 0.1 [L] and 0.75 [L], respectively.

We set a hypothetical condition of driving an actuator by applying 40 [kPa]. As Figure 4 shows, the 0.1 [L] constant volume tank reaches the target pressure of 40 [kPa] with small energy. However, pressure keeps rising after it reaches the required pressure. That is, in order to store the same amount of energy as the 0.75 [L] constant volume tank, the 0.1 [L] tank is required to store higher pressure than the 0.75 [L] tank. The 0.75 [L] tank demonstrates smaller pressure change, but after it supplies air to the actuator, the remaining energy that is unusable for driving the actuator is large.

On the contrary, the initial internal volume of the hollow cylindrical-shaped variable volume tank is small. Therefore, as Figure 3 shows, it reaches the target pressure with a small amount of stored energy. After that, by storing part of the energy of compressed air as elastic energy, it decreases the amount of pressure change. Therefore, the pressure drop in the tank that occurs when the tank supplies air to the actuator can be decreased compared with the conventional constant volume tank.With this effect the compressor does not need to compress air higher than the actuator requires. Since the initial volume is small, remaining air in the tank after supplying air to the actuator can be also decreased. That is, remaining energy is small. These characteristics of the hollow cylindrical-shaped variable volume tank lead to low energy consumption of the entire air supply system.

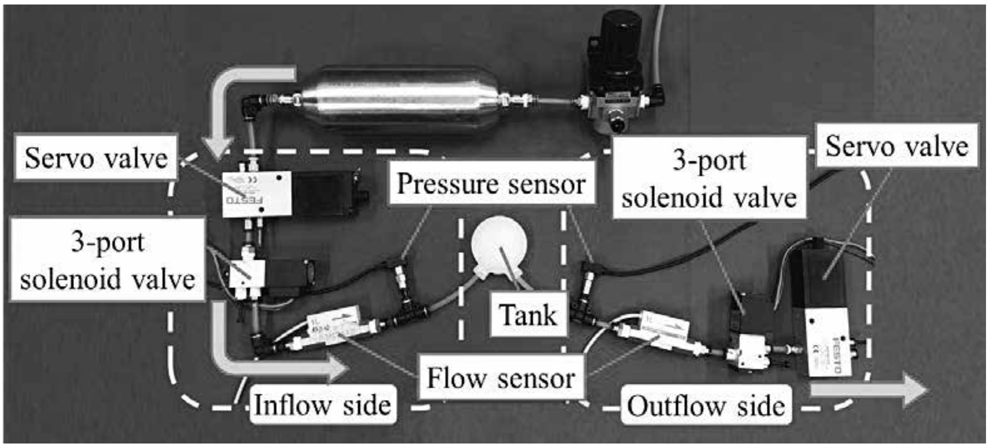


Figure 2. Experimental setup of hollow cylindrical-shaped variable volume tank.

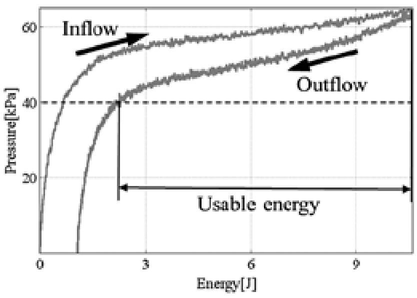


Figure 3. Energy characteristic of hollow cylindrical-shaped variable volume tank.

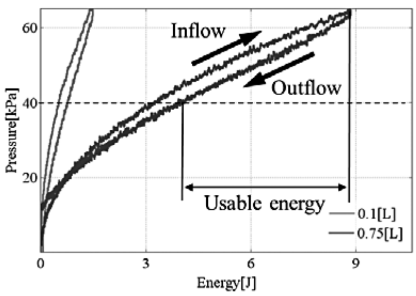


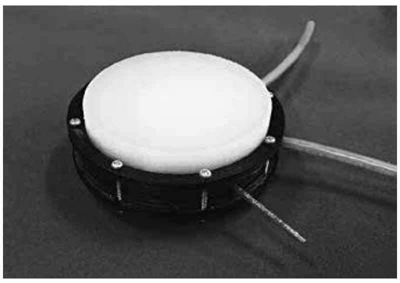
Figure 4. Energy characteristics of constant volume tank.

Ⅲ. Multi-layered variable volume tank

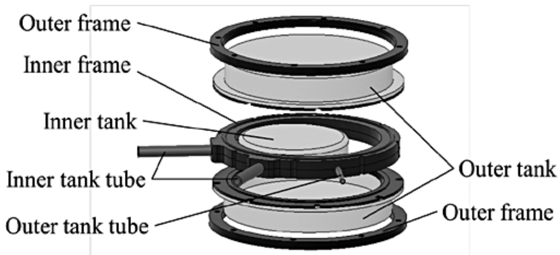
In addition, we propose the multi-layered variable volume tank to improve energy characteristic. In the previous study, the double layer spherical-shaped variable volume tank was developed to increase storable pressure without increase in thickness and weight, but it had large volume. The hollow cylindrical-shaped variable volume tank has small initial volume, as a result, multi-layering the hollow cylindrical-shaped variable volume tank can be smaller than the double layer spherical-shaped variable volume tank. Figure 5 shows the multi-layered hollow cylindrical-shaped variable volume tank. The hollow cylindrical-shaped variable volume tank shown in Figure 1 is used as the inner tank. The inner tank is inserted between two outer tanks. The outer tank has an outer diameter of 92 [mm], a height of 12.6 [mm], and a thickness of 6 [mm]. The expansion of the inner tank is restricted by applied pressure between the inner and outer tanks. As the inner tank expands, pressure between the inner and outer tanks increases. However, pressure change is limited because the outer tank is also a variable volume tank. So, the outer tank presses the inner tank keeping the applied initial-pressure.

We conducted an experiment to measure the energy characteristics of the multi-layered variable volume tank. Prior to the experiment, we measured the energy characteristics of the inner and outer tanks, respectively, using the experimental setup shown in Figure 2 for measuring the energy characteristics of the hollow cylindrical-shaped variable volume tank in the previous chapter. As shown in Figures 6 (a) and (b), we observed that the inner tank demonstrated pressure relaxation at approximately 60 to 75 [kPa], while the outer tank demonstrated pressure relaxation at approximately 35 to 55 [kPa]. If the tanks are pressurized exceeding the upper limits of 75 [kPa] for the inner tank and 55 [kPa] for the outer tank, it may cause permanent damages to the rubber material of the tanks. Therefore, we set the pressure values as the upper limits.

Figure 7 shows the experimental setup of the multi-layered variable volume tank. In the experiment of the energy characteristics of the multi-layered variable volume tank, first, compressed air was supplied to the outer tank using the electro-pneumatic regulator (CKD: EVD-1100-008AN). The outer tank was closed with the manually operated valve. Then, in the method similar to that of the experiment conducted on the hollow cylindrical-shaped variable volume tank, the inner tank was pressurized and exhausted with the servo valve at 0.6 [L/min]. The inflow energy and outflow energy in the inner tank were measured with the flow sensor and pressure sensor. The pressure change of the outer tank, which was generated by expansion of the inner tank, was measured with the pressure sensor.

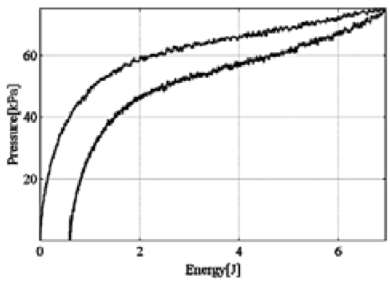


(a) Overview.

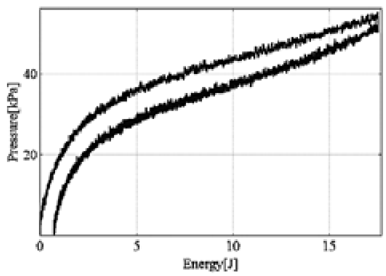


(b) Structure

Figure 5. Multi-layered variable volume tank.



(a) Inner tank.



(b) Outer tank.

Figure 6. Energy characteristics of inner (left) and outer tank (right).

We tried two experimental conditions in applied pressure. To get the difference of 75 [kPa] between the inner tank and the outer tank, which is the upper limit of the applied pressure to the inner tank, 20 [kPa] was applied to the outer tank and air was supplied to the inner tank until it reached 95 [kPa]. 50 [kPa] was applied to the outer tank and air was supplied to the inner tank until it reached 125 [kPa]. Figure 8 shows the energy characteristics of the multi-layered variable volume tank measured under the two conditions. The figure includes the energy characteristic of single hollow cylindrical-shaped variable volume tank as well. As the figure shows, the value of relaxation-pressure and the amount of stored energy improves by multi-layering the tanks. Moreover, the results indicate that the value and amount improve when higher pressure is applied to the outer tank. Figure 9 shows the relationship between pressure in the outer tank and stored energy in the inner tank. As Figure 9 shows, the outer tank keeps the pressure as high as initially applied due to the effect of limiting pressure change. Because of the effect, the pressure of the outer tank does not exceed the outer tank upper limit of 55 [kPa].

Ⅳ. Conclusion

In this paper, the structure and characteristics of the hollow cylindrical-shaped variable volume tank were described. By reducing the internal volume, the tank was downsized and energy characteristics of the tank improved. The results suggest that the hollow cylindrical-shaped variable volume tank leads to low energy consumption of the entire air supply system. We also proposed the multi-layered variable volume tank composed with hollow cylindrical-shaped tanks. The hollow cylindrical-shaped variable volume tank has small initial volume, as a result, the multi-layered hollow cylindrical-shaped variable volume tank can be smaller than the double layer spherical-shaped variable volume tank. The experimental results indicated that the value of relaxation-pressure and the amount of stored energy in the tank increased. These results confirm that the multi-layered hollow cylindrical-shaped variable volume tank will enable us to realize portable air supply systems which can provide high pressure. We will develop the portable air supply system which retrieves and re-compresses exhausted air using the multi-layered variable volume tank.

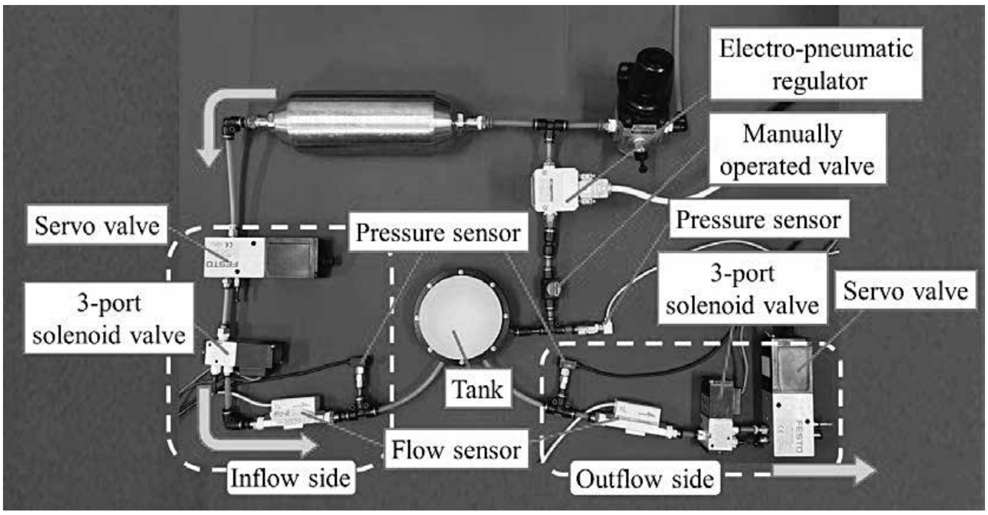


Figure 7. Experimental setup of multi-layered variable volume tank.

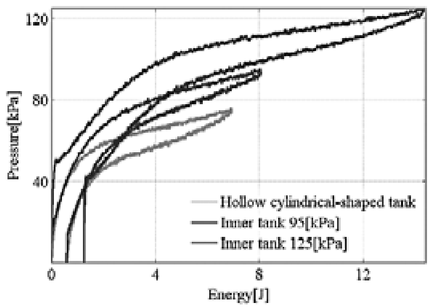


Figure 8. Energy characteristics of multi-layered variable volume tank.

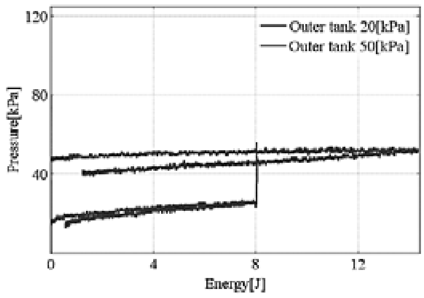


Figure 9. Relationship between pressure in the outer tank and stored energy in the inner tank.

Ⅴ. References

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