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DEVELOPMENT OF SMALL-SIZED AIR PUMP USING BALLOON VIBRATOR FOR WEARABLE DEVICES

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ABSTRACT

This study is aimed at developing a small-sized air pump using an originally contrived balloon vibrator for wearable devices. The developed pump can compress air by vibrating a balloon vibrator which is composed of a doughnut-shaped balloon diaphragm fitted with a circular stainless steel plate. The balloon diaphragm is filled with air. This pump has characteristics as an oil-free, doesn't leak air at all, and has a longer stroke than existed diaphragm pumps. Therefore, this pump is expected to have higher discharge performance than existed diaphragm pumps. In addition, it is also expected to develop an output variable air pump by controlling the inner pressure of balloon. In this paper, the structure of the developed pump is described, and then the fundamental characteristics of this pump are evaluated.

KEY WORDS

Pneumatics, Air pump, Wearable device, Small-sized

NOMENCLATURE

P : Discharge pressure [Pa]
Q : Volumetric flow rate [m^3/sec]
W : Input power to the pump [W]

INTRODUCTION

Recently, many types of movement assist devices have been developed because of the falling birthrate and the aging population [1]. In a perspective of affinity for human, wearable devices using pneumatic rubber muscle have been also developed and have been expected to come into practical use.

To drive these devices, air pumps are required. In order to realize the stand-alone wearable system, air pumps require both high discharge performance and portability. However, existed small-sized air pumps don't have enough discharge performance to drive these devices. So, there have been some studies about the several types of air pumps [2][3][4].

This study is aimed at developing a small-sized air pump using an originally contrived balloon vibrator.

The performance targets of the pump are shown as follow.

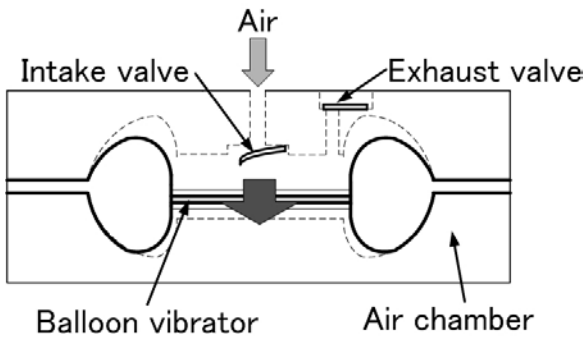
1. Discharge performance
   - Maximum discharge pressure 350[kPa]
   - Maximum flow rate 12.5[Nl/min]

   Both pressure and flow rate are desired to be higher. However, in consideration of the demanded pressure or the response time of wearable devices and the size of the pump, the target performance is decided as above.
2. Size and weight
   - Less than 1[kg] (include controller, etc.)

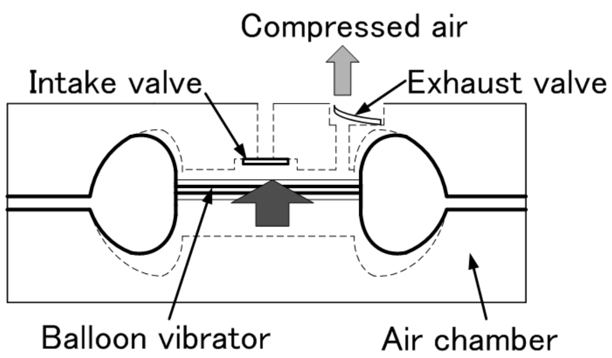
   The size is desired to be small so that the pump is not a burden to people when they equip it on the waist, etc.
3. Noise level
   - Less than 60[dB (A)]

   This noise level corresponds to the noise of normal conversation. But, the noise level is desired to be lower.

In this paper, the structure of the developed pump and characteristics of the balloon vibrator are described, and then the fundamental characteristics of this pump are evaluated. In addition, the application to an output variable air pump is suggested.



(a) Intake air



(b) Exhaust compressed air

Figure 1 Principle of compression

STRUCTURE OF AIR PUMP

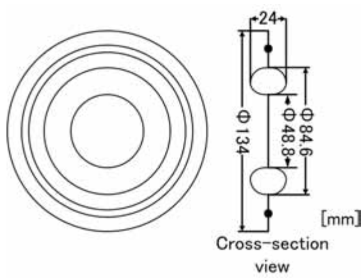
Structure

The developed pump in this study adopts the reciprocating type that is good for reduction in size and weight. And this pump is invented in order to improve defects of piston pumps and diaphragm pumps.

Figure 1 shows the principle of compression of the developed pump. This pump is constructed with an air chamber and a balloon vibrator. The vibrator is composed of a doughnut-shaped balloon diaphragm (shown in Figure 2) fitted with a circular stainless steel plate. The balloon diaphragm is filled with air and serves as a cylinder. By tucking the vibrator with the air chamber and vibrating the vibrator up and down, this pump can compress air.

This pump has characteristics as an oil-free, doesn't leak air at all, and has a longer stroke than existed diaphragm pumps because the vibrator moves using deformation of the balloon diaphragm. In addition, this pump can discharge higher pressure than existed diaphragm pumps because the balloon diaphragm has stiffness by filled with air. Therefore, this pump is expected to have higher discharge performance than existed diaphragm pumps.

Figure 3 shows the structure and the outlook of the prototype pump. This pump lets the balloon vibrator vibrate up and down by an electric motor and compress air. The movable stroke is ±3.5[mm] from the center of the air chamber. As an intake and exhaust valve, flapper valves are attached. And the weight of this pump is 2.6[kg].



(a) Dimension

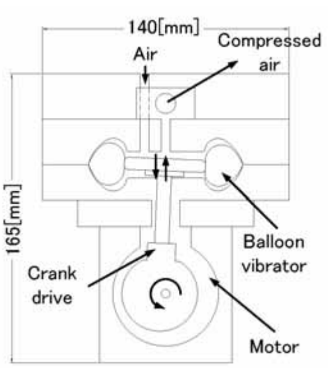
(b) Outlook

Figure 2 Balloon diaphragm

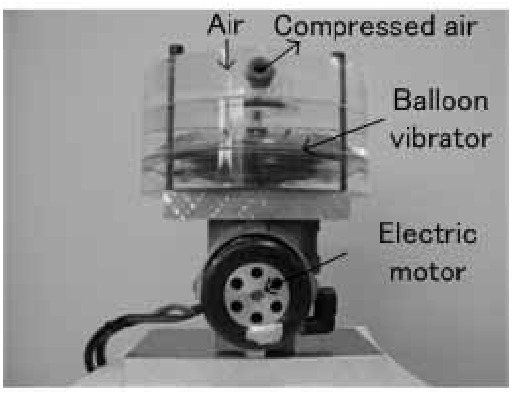
Characteristics of balloon vibrator

The balloon diaphragm has been originally contrived based on deformation analysis. This diaphragm is made of nitrile rubbers, which are generally used for diaphragms. In order to inhibit expansion of balloon when filled with air, fibers are interweaved inside the diaphragm. A tube with a 2[mm] outer diameter is attached on the side of the diaphragm in order to control the inner pressure of balloon. By controlling the inner pressure, the characteristics of the diaphragm can be changed.

Figure 4 shows the relation between the amount of displacement of the balloon vibrator and the resistance force on each inner pressure of balloon. The measuring condition is shown in Figure 5. The resistance force to move the vibrator ±3.5[mm] from the center of the air chamber is measured by the force sensor. Figure 4 shows that the resistance force of the vibrator is linearly related to the amount of displacement, and shows that the inner pressure of balloon changes the stiffness of the balloon diaphragm. Figure 6 shows the stiffness on each inner pressure of balloon. Figure 6 shows that the stiffness is linearly related to the inner pressure of balloon.



(a) Structure



(b) Outlook

Figure 3 Prototype pump

PERFORMANCE EVALUATION

Experimental system

To evaluate the performance of the developed pump, discharge pressure, flow rate and input power are measured. The experimental system is shown in Figure 7. The revolution speed is set at every 500[rpm] from 1000[rpm] to 3000[rpm]. The inner pressure of balloon is set at every 40[kPa] from 0[kPa] to 200[kPa] and controlled by the electro-pneumatic regulator manufactured by CKD. PA-103G manufactured by COPAL as pressure gauges, SEF-52 manufactured by STEC as a flow meter, and WT200 manufactured by Yokogawa Electric as a wattmeter are used for this experiment.

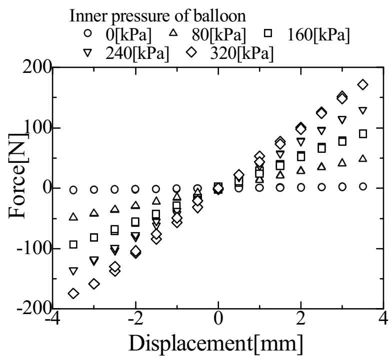


Figure 4 Relation between displacement and force

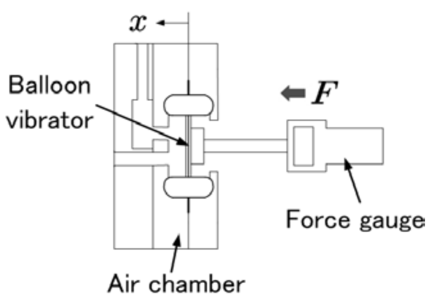


Figure 5 Measuring condition

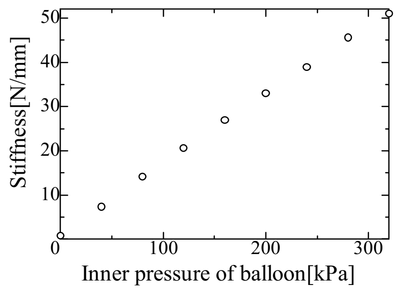


Figure 6 Characteristics of stiffness

Fundamental characteristics

Figure 8, 9, 10, 11 and 12 show the discharge performance and the pump efficiency of the developed pump on each revolution speed. Each figure shows the measurement result in the normal operation of the motor. The pump efficiency η is calculated using Eq. (1).

$$\eta = \frac{P \times Q}{W} \qquad (1)$$

From the figures, the maximum discharge pressure is about 250[kPa](the revolution speed 2000[rpm], the inner pressure of balloon 200[kPa]), the maximum flow rate is about 57[Nl/min](the revolution speed 3000[rpm], the inner pressure of balloon 200[kPa]), and the maximum efficiency is about 90[%](the revolution speed 2000[rpm], the inner pressure of balloon 200[kPa]). Therefore, the suggested pump mechanism using a balloon vibrator serves as the air pump well.

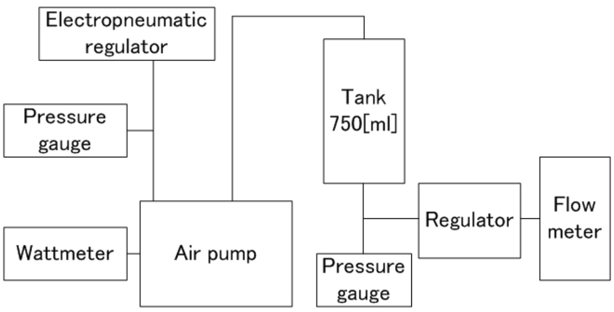


Figure 7 Experimental system

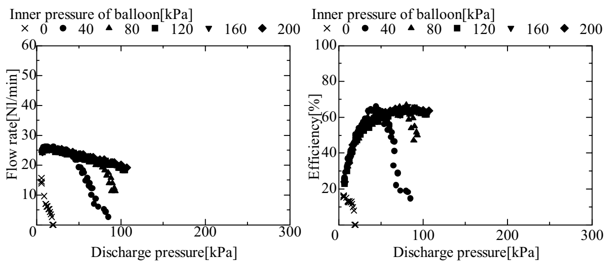


Figure 8 Characteristics of the pump (1000[rpm])

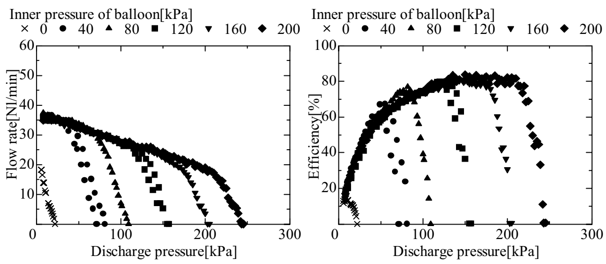


Figure 9 Characteristics of the pump (1500[rpm])

However, if the discharge pressure becomes higher than the inner pressure of balloon, the discharge performance comes down. When the discharge pressure becomes higher than the inner pressure of balloon, the balloon diaphragm gets dented and the volume of inside of the air chamber increases. The discharge volume by vibrating the vibrator decreases as much as the volume of inside of the air chamber increases. This is the reason why the discharge performance comes down.

In order to compare with the developed pump, the performance of an existed pump for medical use (shown in Figure 13) is evaluated too. The experimental system is the same as the developed pump. Figure 14 shows the discharge performance of the existed pump. From the figures, the maximum discharge pressure is about 280[kPa](the revolution speed 1500[rpm]), the maximum flow rate is about 55[Nl/min](the revolution speed 3000[rpm]), and the maximum efficiency is about 80[%](the revolution speed 2000[rpm]). Though the developed pump is inferior in the discharge pressure, it is comparable in the flow rate and superior in the pump efficiency to the existed pump.

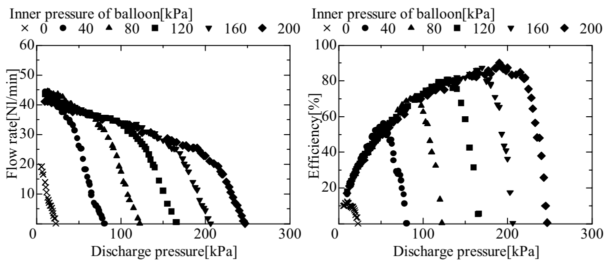


Figure 10 Characteristics of the pump (2000[rpm])

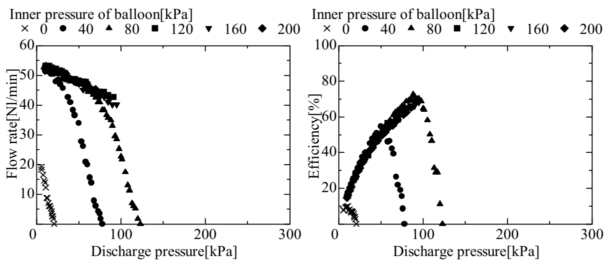


Figure 11 Characteristics of the pump (2500[rpm])

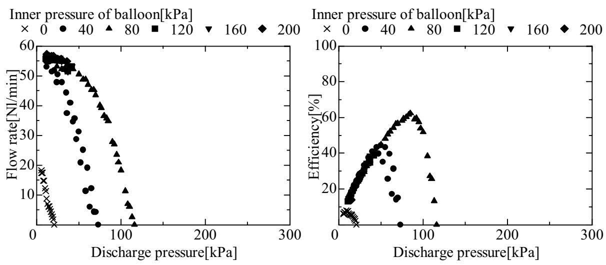
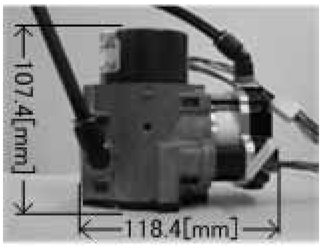


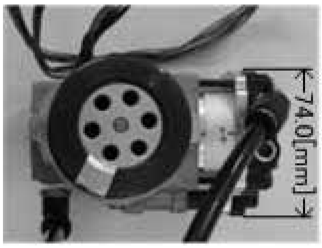
Figure 12 Characteristics of the pump (3000[rpm])

Application to output variable air pump

Figure 15 shows the discharge volume per cycle. Though the maximum volume is about 0.025[Nl/cycle], the volume tends to decrease as the revolution speed increases. It is thought that flapper valves don't work well at the high revolution speed. Therefore, it is needed to consider the size, the configuration, and the mounting location of the valves.



(a) Side view



(b) Top view

Figure 13 Outlook of existed pump

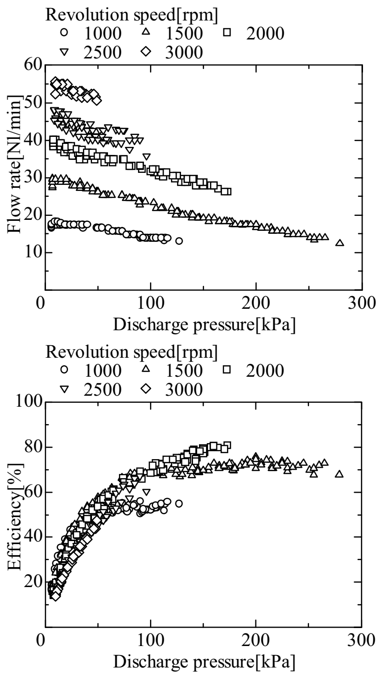
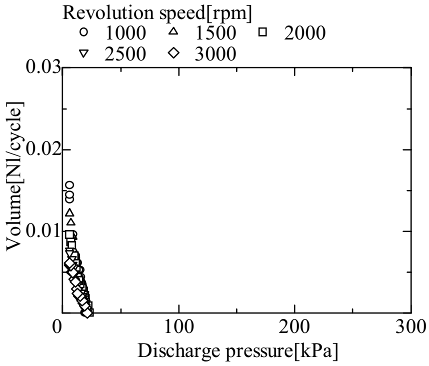
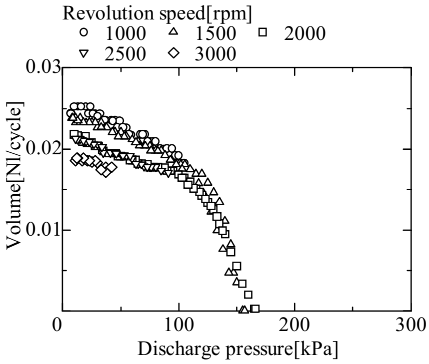


Figure 14 Characteristics of existed pump

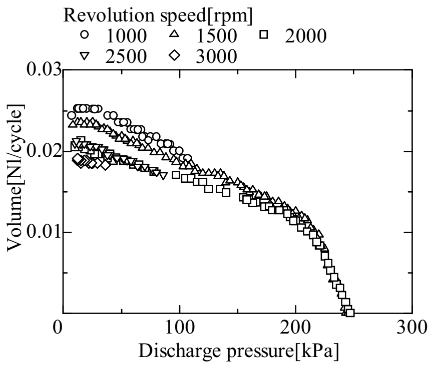
From the figures, the discharge pressure doesn't depend on the revolution speed but the inner pressure of balloon. Therefore, the developed pump can meet various uses only to change the inner pressure of balloon without changing the mechanical structure. In addition, it is expected to apply to an output variable pump that can change the discharge performance continuously by controlling the inner pressure of balloon.



(a) Inner pressure of balloon 0[kPa]



(b) Inner pressure of balloon 120[kPa]



(c) Inner pressure of balloon 200[kPa]

Figure 15 Relation between pressure and volume

So, the discharge pressure is measured in setting the revolution speed 2000[rpm], the flow rate 0[Nl/min], and changing the inner pressure of balloon every 40[kPa] in a step from 0[kPa] to 200[kPa]. The discharge pressure is changed continuously by changing the inner pressure of balloon as shown in Figure 16.

In order to realize the output variable pump, it is needed to use compressed air which the developed pump itself discharges to control the inner pressure of balloon. It means the inner pressure of balloon is less or equal to the discharge pressure. Therefore, it is needed to consider the control method, even as to look into the possibility more.

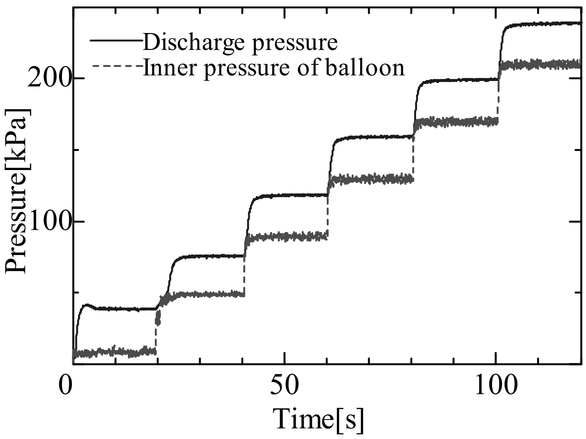


Figure 16 Output variable air pump

CONCLUSION

In this paper, it is described about the air pump using the balloon vibrator for wearable devices and shown that the suggested pump mechanism serves as the air pump well from the performance experimentally evaluated. The balloon diaphragm originally contrived has a linear stiffness and the inner pressure of balloon can control the discharge performance. These characteristics are very useful functions for the design of the air pump.

Issues for the future are shown as follow.

- The design of the most suitable air chamber and the select of the most suitable motor for the reduction in size and weight in order to use for wearable devices.
- The design of the most suitable valves to improve intaking and exhausting air
- The test and improvement of the durability of the balloon diaphragm
- The reduction of noise level and vibration
- The invention of control method for the output variable pump.

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