Unconstrained Vibrational Pneumatic Valves for Miniaturized Proportional Control Devices

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Abstract

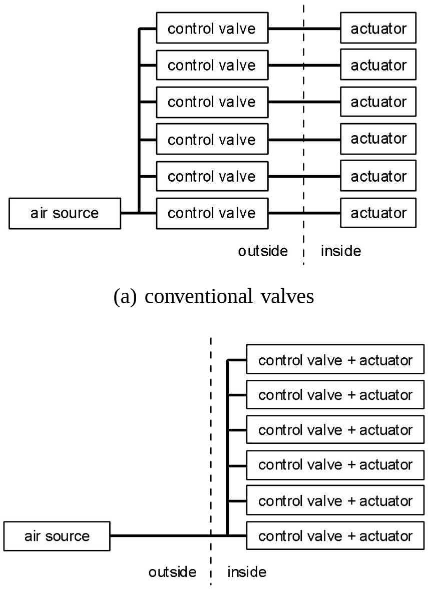
We have designed and tested a new type of pneumatic valve which is very small and may be ideal for use in, for example, wearable robots. The valve, called an unconstrained vibrational valve, is novel in that the poppet is not mechanically constrained. The valve is opened and closed by turning on and off a piezo-electric actuator which vibrates to make the poppet move. The valve does not need precise engineering, making it easy to miniaturize, and requires fewer air tubes, making it more practical for use in a wearable robot. In this study, to help us optimize the valve, we designed and tested three variations of the valves based on theoretical flow rate models. One of the valves, which has an orifice 2.0 mm in diameter and a metal poppet 6.0 mm in diameter would be able to create the necessary pressure changes in a vessel of dimensions volume to a McKibben tube used in wearable robots.

Key words— Pneumatic valve, Vibration, Proportional control valve, Miniaturization, Air flow

1. Introduction

There is currently much interest in the development of ”wearable robots”, that is, mechanical devices that people with, for example, muscle dysfunction, can literally wear to help them move their limbs [1] [2] [3]. Though pneumatic actuators [4] such as McKibben tubes [5] [6] and HRAs [7] are themselves light and powerful, they require bulky pneumatic valves to control the air flow or pressure applied to the actuators. Moreover, the tubes connecting the pneumatic actuators and control valves often present a ”tube spaghetti” problem, as shown in Fig.1-(a), hindering the use of a wearable robot.

The goal of our research, therefore, was to design a miniaturized light-weight control valve that can be installed into a pneumatic actuator. By integrating the control valve and the pneumatic actuator, the spaghetti problem can be eliminated because the distribution of the air flow becomes simpler, as illustrated in Fig.1-(b). Additionally, because the distance between the control valve and the actuator is shortened, response is faster.



(a) conventional valves

(b) miniaturized valves

Fig. 1. Effect of miniaturized valves

Control valves consist of a sensor, a control circuit and an ON/OFF valve. Thanks to MEMS and LSI technologies [9], a miniaturized air pressure sensor [8] and a micro-processor are available. A bottleneck against the miniaturization of a control valve lies in a pneumatic ON/OFF valve. As shown in Fig.2, commercial proportional control valves can provide sufficient air flow for a wearable robot, but they are too heavy [10]. Many MEMS valves have been proposed [11] [12] but they cannot provide enough air flow for a wearable robot. A few miniaturized proportional control valves are now under development [13].

In this article, we describe the problems of miniaturizing pneumatic control valves. We describe a new type of pneumatic valve, an ”unconstrained vibrational valve”. Section 2 describes the principle of the new valve, and Section 3 describes the model of the air flow

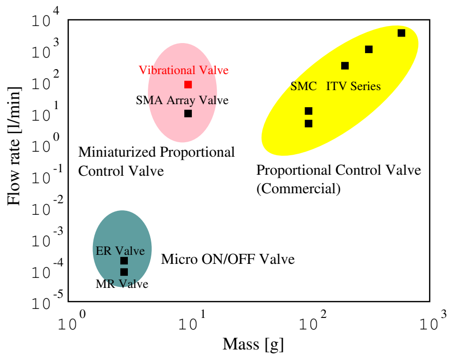


Fig. 2. State of the arts

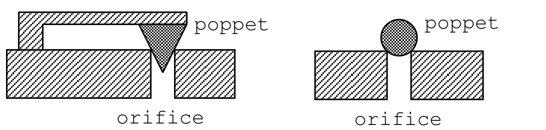
in the proposed valve. Section 4 shows experimental evaluations of the flow rate model and the unconstrained vibrational valve.

2. Unconstrained Vibrational Valve

2. 1 Principle

The structure of a conventional poppet valve is illustrated in Fig.3-(a). The valve is opened and closed by the poppet being moved by an actuator attached to a beam. Thus, the poppet is structurally constrained, and its position relative to the orifice is changed by the actuator. Miniaturization of such a constrained valve is difficult because very accurate relative positioning of the poppet and orifice is required, and this makes it vulnerable to heat distortion which could result in air leakage.

To overcome these drawbacks, we designed a valve (see Fig.3-(b)) in which there is no structural constraint between the poppet and orifice. The proposed design does not require high positioning accuracy in the assembly, and moderate temperature changes have little effect. Thus, this structure can be miniaturized easily. Moreover, this simple setup reduces the cost.



(a) constrained-poppet valve (b) unconstrained-poppet valve

Fig. 3. Orifice and poppet

The force of the air supply acts to lodge the poppet into the entrance of the orifice, and thus acts to close the valve. We open the valve by applying a counteracting force or, actually, a series of counteracting forces generated by a vibrating actuator. This simple structure can be miniaturized easily.

2. 2 Designs

To optimize the unconstrained vibrational valve, we designed and tested three variations.

Design 1: The first of these is shown in Fig.4. The cylinder inside the case is divided into the supply side and the output side by a structure with an orifice. The poppet, a metal ball, is on the supply side, and the vibration actuator is on the output side. The rubber O-ring prevents the gap between the supply and output sides.

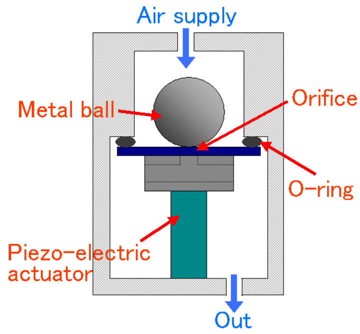


Fig. 4. Design 1 for vibrational valve

A prototype is shown in Fig.5. The vibration actuator is an NEC Tokin piezo-electric actuator AE0203D08 (see Fig.6), driven by a rectangular wave applied to an FET circuit. When the actuator is off, the air supply forces the metal ball against the orifice, closing it, as shown in Fig.7-(a). When the actuator is on, the metal ball vibrates up and down, allowing air to pass through the orifice, as shown in Fig.7-(b).

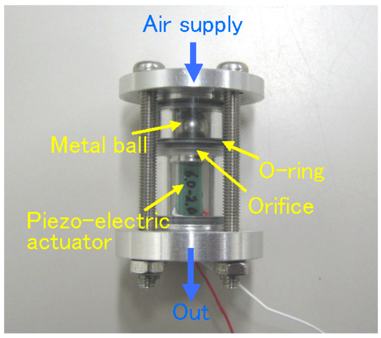


Fig. 5. Prototype of Design 1

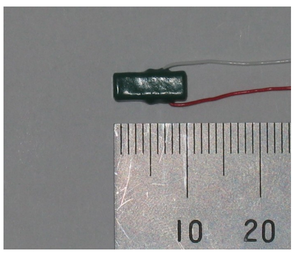
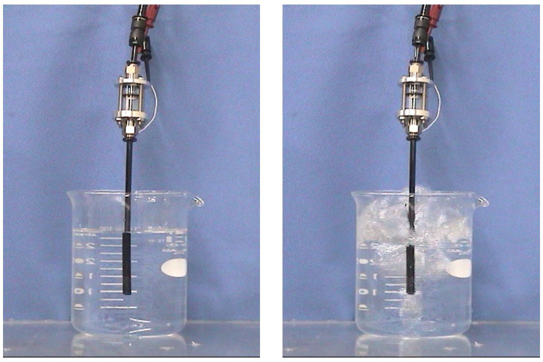


Fig. 6. Piezo-electric actuator for vibration

Design 2 is shown in Fig.8. The design is similar to Design 1, but it lacks the O-ring, improving the



(a) Actuator off: valve closed (b) Actuator on: valve open

Fig. 7. Operation of Design 1

transmission of the actuator's vibrations to the metal ball. The air that passes through the orifice exits the valve via a flexible tube.

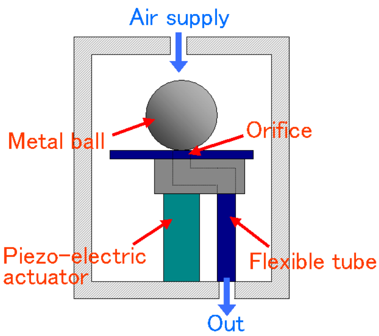


Fig. 8. Design 2 for vibrational valve

A prototype is shown in Fig.9. As with Design 1, the valve is closed when the actuator is off (Fig.10-(a)), and open when the actuator is on (Fig.10-(b)).

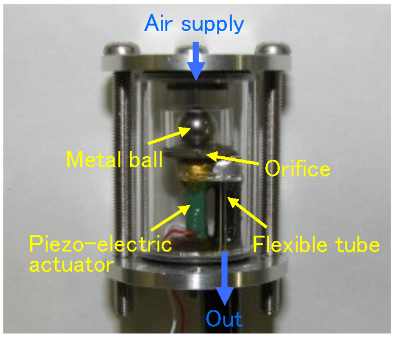
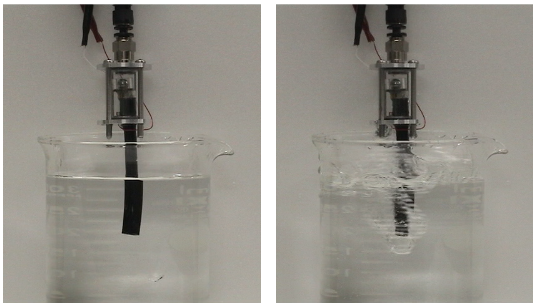


Fig. 9. Prototype of Design 2

Design 3: The third design is shown in Fig.11. Like Design 2, it also has a flexible tube but, unlike Design 2, this tube is arranged so that it cannot hinder the vibration of the actuator.

A prototype is shown in Fig.12. As with Designs 1 and 2, the valve is closed when the actuator is off (Fig.13-(a)), and open when the actuator is on (Fig.13-(b)).



(a) Actuator off: no air flowing (b) Actuator on: air flowing through the water

Fig. 10. Operation of Design 2

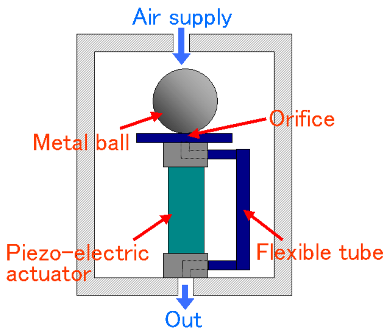


Fig. 11. Design 3 for vibrational valve

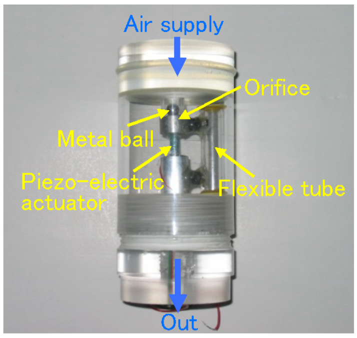
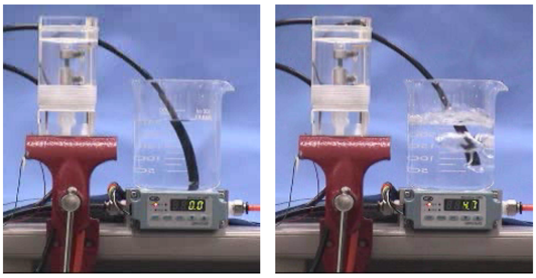


Fig. 12. Prototype of Design 3

3. Modeling of Air Flow

We investigated theoretically the effects of miniaturizing the valve on the air flow. We want the cross-sectional area of the orifice to be the minimum required for the necessary flow rate. Let us investigate the relationship between the cross-sectional area of an orifice and the flow rate.

Let V be the volume of a vessel and P_0 be the initial pressure inside it. Let us increase the internal pressure from P_0 to $P_0 + P_{\mathrm{desired}}$ in time t by applying an air flow



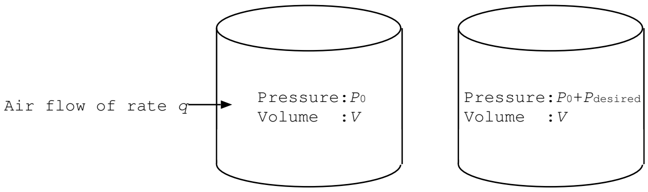
(a) Actuator off: no air flowing (b) Actuator on: air flowing through the water

Fig. 13. Operation of Design 3

at a rate q, as shown in Fig.14. From Boyle's law, we can write:

$$q = \frac{P_{\mathrm{desired}} V}{P_0 t} \times \frac{T_0}{T} \ . \qquad (1)$$

Multiplication of $T_0/T \ \ (T_0 = 273\mathrm{K})$ yields the standard flow rate.



(a) initial (b) time t

Fig. 14. Apply pressure to vessel

Let us determine the orifice cross-sectional area that satisfies the calculated flow rate. Fig.15 shows an ideal orifice. Let u_1 and u_2, and p_{u} and p_{d} be the velocities and pressures on the up and downstream sides, respectively. Suppose that u_1 is much smaller than u_2. Let R be the molar gas constant, κ the specific heat ratio of air (κ=1.4), and ρ the density of air (ρ=1.2928g/l). Let a be the cross-sectional area of the orifice. The minimum sectional area to realize flow rate q is given by

$$a = \frac{q\rho}{p_{\mathrm{u}}} \sqrt{\frac{RT}{2}} \frac{1}{f(z)} \ . \qquad (2)$$

where

$$f(z) = \begin{cases} \sqrt{\dfrac{\kappa}{\kappa - 1}(z^{2/\kappa} - z^{(\kappa+1)/\kappa})} & (0.528 \le z \le 1) \\ \sqrt{\dfrac{\kappa}{\kappa - 1}\left(\dfrac{2}{\kappa + 1}\right)^{2/(\kappa-1)}} & (z < 0.528) \end{cases}$$

and z is the pressure ratio $p_{\mathrm{d}}/p_{\mathrm{u}}$. Note that $f(z)$ is constant when $z < 0.528$ and decreases monotonically otherwise [14].

By specifying pressure increment P_{desired} and time t, we can calculate flow rate q using eq.(1). Then, we can determine the minimum area a using eq.(2).

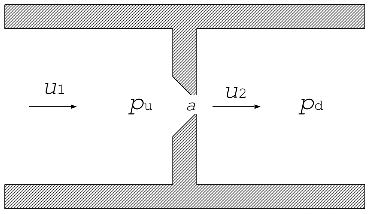


Fig. 15. Orifice model

4. Experimental Evaluation

We determined the requirements to miniaturize the control valves. When we supply 0.5 MPa pressure into a vessel with an inner diameter of 34 mm and a height of 30 mm, the pressure inside the vessel would have to increase from 0.0 MPa to 0.2 MPa in 0.1 s.

4. 1 Model verification

We verified the requirements presented in the previous section. Substituting P_{desired} = 0.2 MPa, V = 27237 mm^3, P_0 = 0.1 MPa, and T = 296.8 K, we get $q \approx 29.8$ l/min .

We verified the above calculation experimentally using the vessel with an inner diameter of 34 mm and a height of 30 mm. The change in the internal air pressure with time when the pressure of the air supply was 0.5 MPa and flow rate was 29.8 l/min is shown in Fig.16 The internal pressure increased from 0.0 MPa to the desired value 0.2 MPa in 0.095 s. Hence, the required flow rate is 29.8 l/min.

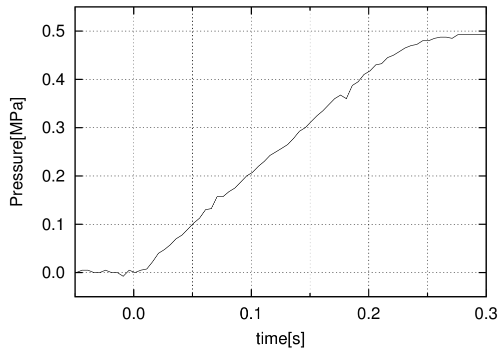


Fig. 16. Pressure during air supply

Assuming that $z < 0.528$, substituting into eq.(2) p_{u}=0.5MPa, T=300K, and flow rate q=29.8l/min, we get:

$$a \approx 0.55 \ \ \mathrm{mm}^2 \ .$$

Thus, the cross-sectional area of the orifice can be reduced to 0.55 mm^2. For a circular orifice, the diameter works out to be 0.84 mm.

We verified this calculation experimentally. For a circular orifice 0.8 mm in diameter, the relationship between the pressure ratio $z = p_d/p_u$ and flow rate q was as shown in Fig.17. The flow rate is constant for *z* is below 0.528. The theoretical constant flow rate is 27.4 l/min, while the empirical value is 30.0 l/min. The discrepancy may be due to the orifice being slightly larger than 0.8 mm in diameter. Hence, an orifice of diameter 0.84 mm is sufficient.

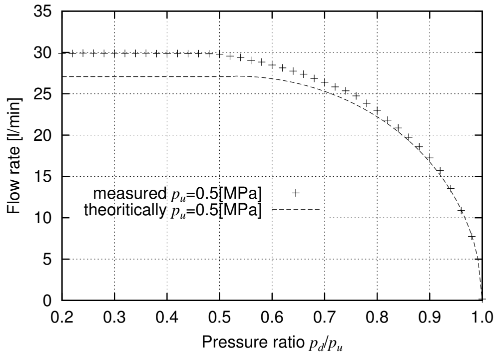


Fig. 17. Pressure ratio - flow rate diagram

4. 2 Evaluation of three designs

We experimentally evaluated the three designs. We tested Prototype 1, that is, the prototype of design 1, with an orifice 2.0 mm in diameter and a metal ball 6.0 mm in diameter. The input air pressure was 0.5 MPa and the voltage applied to the actuator was a rectangular wave of 0-40 V. We observed how the flow rate changed with the frequency at which the actuator vibrated. The results are shown in Fig.18. As can be seen the vibration could control the opening and closing of the valve but, unfortunately, the relationship between the flow rate and the vibration frequency is sporadic. Moreover, the flow rate is much lower than the required rate. The low flow rate and its irregular change with frequency may be caused by the O-ring used for sealing the orifice.

Prototype 2 had the same orifice and poppet, and the same pressure and voltage, as in Prototype 1. The relationship between the flow rate and the vibration frequency is shown in Fig.19. The flow rate is higher than it was for Prototype 1, probably because of the absence of the O-ring. Unfortunately, the relationship between the flow rate and the vibration frequency is still sporadic.

Prototype 3 had the same orifice and poppet, and the pressure and voltage were the same as in the other two prototypes. The relationship between the flow rate and the vibration frequency is shown in Fig.20. The flow rate tends to be higher than in Prototype 1, and less sporadic than in Prototype 2. The flow rate shows three peaks at a frequency of about 2.0, 2.8 and 4.0 kHz.

We conclude that the vibration of the piezo-electric actuator is more effective in the third prototype.

The flow rate can be controlled because it is driven in the vicinity of the peak and uses PWM control. Moreover, it may be feasible to control multiple valves with one piezo-electric actuator if the peak frequency changes according to the sizes of the metal ball and orifice. Thus, further miniaturization by composing two (one for supply and the other for exhaust in a proportional control valve) of one actuator becomes a possibility.

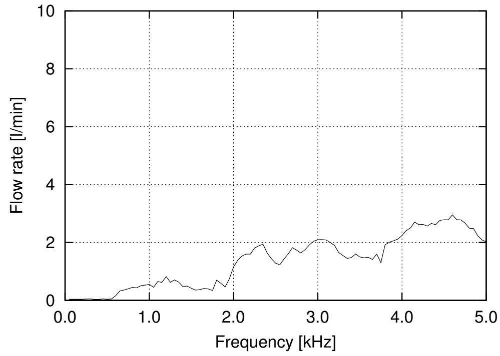


Fig. 18. Flow rate - frequency relationship in the first design

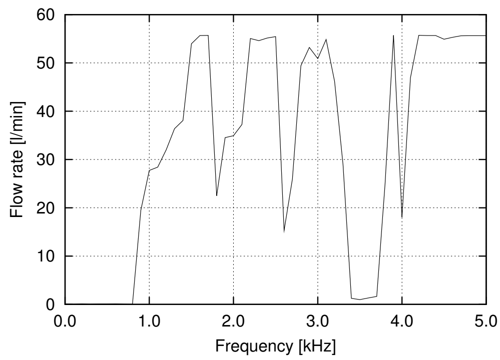


Fig. 19. Flow rate - frequency relationship in the second design

5. Concluding Remarks

We proposed a new ON/OFF valve, namely an unconstrained vibrational valve, for the miniaturization of a pneumatic control valve. The valve can be opened and closed by causing the mechanically unconstrained poppet to move by vibrations induced by an actuator. We experimentally confirmed the requirements for the valve to function in a vessel 34 mm in diameter and 30 mm in height when the pressure is increased from 0.0 MPa to 0.2 MPa in 0.1 s. We formulated the air flow in an ON/OFF valve to investigate theoretically how the ON/OFF valve can be miniaturized. We found that the cross-sectional area of the orifice should be 0.55 mm^2. We verified experimentally that this orifice meets the requirements.

Finally, we assessed our designs using three prototypes. We found that the flow rate of the proposed valve varies with the driving frequency. This suggests that multiple valves can be controlled by a single vibrational actuator. We will employ MEMS technology for the miniaturization of our unconstrained ON/OFF valves to

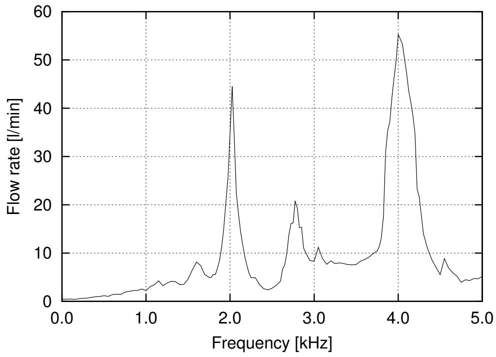


Fig. 20. Flow rate - frequency relationship in the third design

construct small pneumatic control valves for wearable robots.

We are going to evaluate the flow rate - frequency relationships for an orifice and a metal ball of various sizes using Design 3 to establish the dynamic model of an unconstrained vibrational valve.

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