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Design and evaluation of orifice arrangement for particle-excitation flow control valve

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ABSTRACT

In this article, we report a new particle-excitation flow control valve. The purpose of this study is the development of a particle-excitation flow control valve that can precisely control pneumatic cylinders. We have reported this flow control valve principle. The valve, driven by a PZT vibrator, has a simple lightweight structure with large flow rate. We report the relationship between the orifice arrangement and flow rate characteristics of the valve. We have designed a new prototype for the purpose of high controllability. We have measured flow-rate characteristics and confirmed the conditions necessary for continuous adjustment of flow quantity. The control valve works successfully to realize a change in flow rate.

1. Introduction

Small speed control valves to be mounted on cylinder ports are widely used for controlling pneumatic cylinder. Because they can control air flow near the cylinder, the compressibility effect of air can be reduced. However, conventional speed controllers cannot accurately control the airflow rate. For accurate cylinder control, we are developing a valve that can continuously adjust the air flow and be mounted on a cylinder. Several new pneumatic valves have been developed to improve the control of the cylinder [1–6]. The aim of these researches are miniaturization [1–4], low-power driving [5] and high-responsiveness [6]. The control systems of pneumatic cylinder have been developed [7–11]. These approaches are the use of the PZT actuator [7,8] and the controls of the valve [9–11]. The authors have been developing new pneumatic control system for simplification of the conventional pneumatic system [12].

We proposed a new flow control valve using particle excitation with a bulk lead zirconate titanate (PZT) vibrator. The flow control valve consists of an orifice plate which has some orifices, PZT vibrator, and iron particles to caulk orifices. The flow rate of this valve can be controlled by exciting particles which close orifices. This valve is small, simple, and controls a wide range of flow rates. It can be used as a small speed controller mounted on pneumatic cylinders and as a small pneumatic flow control valve for general purposes. We have proposed the principle and basic structure of the new valve and showed experimentally its potential using the first functional prototypes in the previous article [13].

We have evaluated several prototype designs of this valve [14,15] to find the most practical orifice design, including orifice arrangement, orifice size, and vibration mode of the orifice plate. As achieving continuous flow rate control was not easy and the valve often causes unreliable operation and poor flow capacity in the previous research, we optimize the diameter and arrangement pattern of orifices for realizing continuous flow rate control in this report. Firstly we propose a new orifice condition which are orifices pattern and orifices diameter for continuous flow control. Next, we confirm the relation between the orifice arrangement and flow-rate characteristics by the experiments. Finally we observe the particles movement by changing flow rate.

2. Working principle

The working principle and basic structure of the particle-excitation flow control valve we proposed in the previous article [13] are shown in Fig. 1. This structure is simple and suitable for reducing valve's weight and size. Our flow control valve consists of an orifice plate, a PZT vibrator, and iron particles. Fig. 1a shows the closed state of the valve. By supplying air pressure, the air flow carries and deposits particles over the orifice. This valve is normally closed because particles seal the air flow. Fig. 1b shows the opened state of the valve. In this state, the excitation of the orifice plate by the PZT vibrator moves the particles away from the orifice plate. As a result, a space is generated between the particles and orifices and air flows through them. The intensity of the excitation controls the

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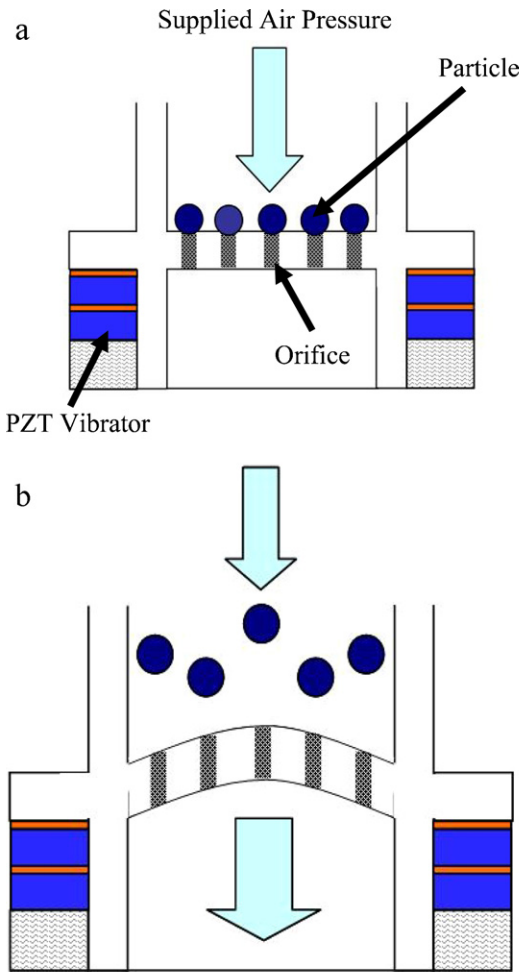

Fig. 1. Structure of new variable orifice (a) closed state and (b) opened state.

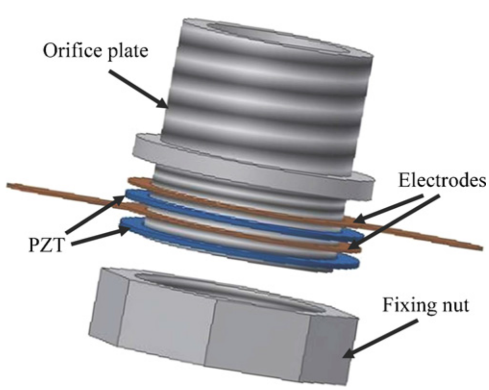

Fig. 2. Schematic of flow control valve.

flow rate. The typical response times of the prototypes are about 30 ms for opening and about 120 ms for closing [16].

The drive condition of the valve is calculated using dynamic balance equations. When air flow carries and deposits particles over the orifice, the pressing force of the particles is calculated using the following equation.

$$F_1 = \pi r^2 P \pm mg \quad (1)$$

where F_1 is the pressing force of the particles, P is the supplied air pressure, r is the radius of an orifice, m is the particle mass, and g is the acceleration of gravity. In this equation, ± depends on the installation direction of the valve. $\pi r^2 P$ is generally much larger than mg for a pressure higher than 0.50 MPa; $\pi r^2 P$ = 1.05 N, mg = 0.21 × 10^{-4} N for the typical values of r = 0.25 mm, P = 0.50 MPa, and m = 2.10 × 10^{-6} g, for example. Thus, the effect of gravity is small. In fact, our developed valve works well in any orientation and with any particles.

The dynamic force of the particles applied by the PZT vibrator depends on the particle mass, displacement, and input frequency, which is expressed by:

$$F_2 = -A\omega^2 m \quad \sin \quad \omega t \quad (2)$$

where F_2 is the dynamic force, A is the amplitude of particles, and ω is the angular frequency when the driving frequency f is defined as $\omega = 2\pi f$. A is the same value of the orifice plate displacement on condition that the particles remain on orifice plate. If F_2 is larger than F_1, the particles are moved away from the orifices.

Table 1
Necessary particle excitation a.

r (mm)	0.25	0.20	0.15
a (m/s^2)	6.63 × 10^4	4.31 × 10^4	2.35 × 10^4

Table 2
Resonance frequency and max flow rate of pattern 1.

Radius of an orifice (mm)	Resonance frequency (kHz)	Max. flow rate (l/min)
0.5	150.4	84.0
0.4	186.3	77.1
0.3	186.2	57.6

Table 3
Resonance frequency and max flow rate of pattern 2.

Radius of an orifice (mm)	Resonance frequency (kHz)	Max. flow rate (l/min)
0.5	190.5	80.0
0.4	191.1	74.0
0.3	190.1	54.3

Table 4
Resonance frequency and max flow rate of pattern 3.

Radius of an orifice (mm)	Resonance frequency (kHz)	Max. flow rate (l/min)
0.5	192.3	77.9
0.4	192.1	65.2
0.3	191.2	48.2

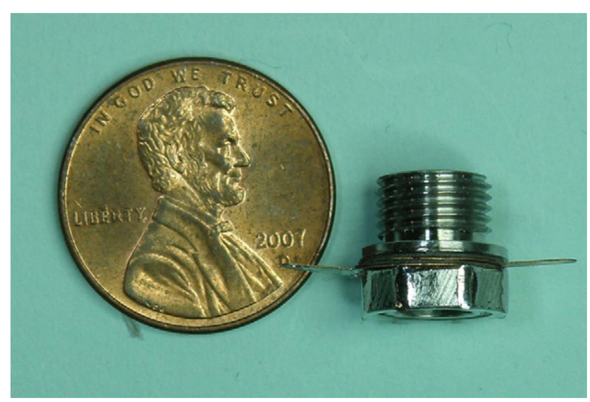

Fig. 3. Assembled flow control valve.