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Paper:

Development of Novel Particle Excitation Flow Control Valve for Stable Flow Characteristics

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The authors have previously developed a compact, light-weight air flow control valve, which realizes continuous flow control. The vibration produced by a piezoelectric device (PZT) was used to excite particles confined in a flow channel to control the valve opening for the developed control valve. Therefore, the voltage applied to the PZT can be changed to continuously control the flow rate. A new working principle was developed for the control valve to stabilize flow rate characteristics. Different types of particles were used to change the valve opening condition. A prototype was manufactured to demonstrate the effectiveness of the control valve.

Keywords: pneumatic actuator, flow control valve, PZT, transducer

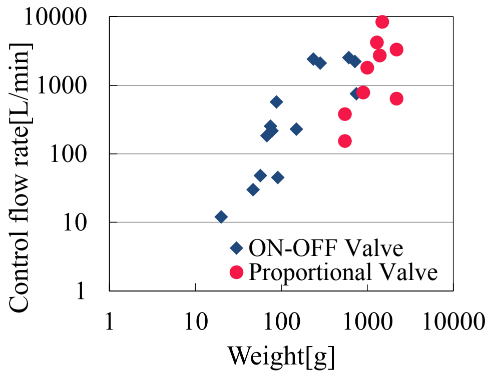


Fig. 1. Relationship between the control flow rate and the valve weight.

1. Introduction

Pneumatic actuators are lighter and less expensive than hydraulic actuators or electromagnetic motors, and are widely used at factories and manufacturing facilities. Pneumatic actuators are also explosion-resistant and safe and satisfy compliancy requirements. Hence, they are used for power assist equipment [1–2]. Recently, several studies were conducted on soft actuators and their applications in medical equipment and rehabilitation [3–6]. Studies have also examined the application of the actuators as an artificial muscle in power assist equipment [7–9]. However, it is difficult to control pneumatic equipment since air is compressible and has nonlinear characteristics. Therefore, continuous flow control is necessary for the stable driving of pneumatic equipment. **Fig. 1** shows the relation between weight and control flow rate of a commercially available pneumatic control unit. Pneumatic control units could be roughly classified into ON-OFF valve type and proportional control valve type. The ON-OFF valve has high responsiveness and large control flow rate per unit weight. However, it cannot control air flow continuously. The proportional control valve is a pneumatic control unit with output proportional to the applied voltage or control current. It can control the flow rate continuously. However, most commercially available proportional valves are large, as shown in **Fig. 1**. Presently, the ON-OFF valves are commonly used for the air control. Many studies investigated ON-OFF valves in air control. For example, PWM control was studied in the use of ON-OFF valves for continuous flow control [10–12]. Studies also examined the use of multiple compact ON-OFF valves for continuous output [13–14]. The compactification of control valves and improvement of controllability were also evaluated by researchers [15–17]. In a previous study, a compact, light-weight flow control valve was developed by using a piezoelectric device (PZT) [18–20]. The developed control valve was compact and could achieve continuous flow control. In this study, a working principle of the control valve for maintaining stable and continuous flow characteristics was proposed by extending the working principle of the developed control valve. A prototype was made and its characteristics were examined.

In this paper, the basic principle of the developed control valve and the proposed new working principle for stable flow control are examined and detailed. Next, the structure of the developed control valve prototype and the basic characteristics of the prototype measured experimentally are presented. In the experiments, the principle of stable flow characteristics was evaluated and stable flow output was successfully achieved. The responsive-

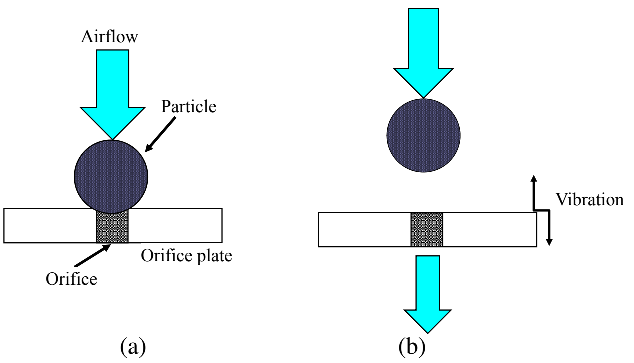


Fig. 2. Basic working principle of the valve.

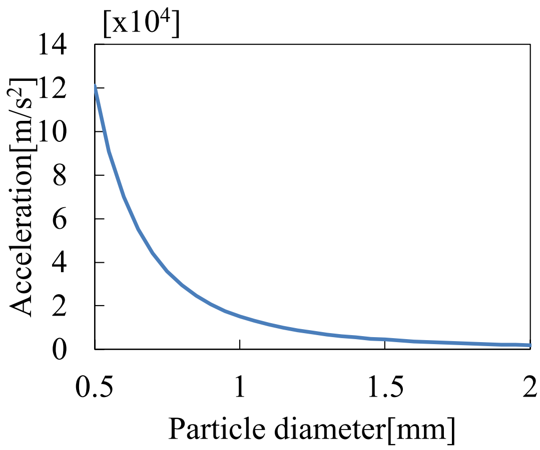


Fig. 3. Relationship between particle diameter and necessary acceleration.

ness at flow switching was also evaluated. The results indicate that the proposed working principle is effective in stabilizing the flow characteristics.

2. Working Principle of Novel Valve

2.1. Basic Working Condition

The authors have previously developed a control valve with particles used as valve elements. In the valve, the valve opening was controlled by the vibration control of a PZT [18–19]. **Fig. 2** shows the basic principle of a control valve using vibrations. As shown in **Fig. 2(a)**, a particle is pressed onto the orifice opening under the application of air pressure. The particle closing in the orifice prevents the air from leaking to the outside. The particle on the orifice also vibrates if a PZT produces vibration on the orifice plate. As in **Fig. 2(b)**, the particle moves away from the orifice when the external force from the vibration exceeds that of the air pressure. As a result, the orifice opens and the air can flow through it. This structure does not require the valve element positioning mechanism or the valve element fixing mechanism, and the control valve can be made lighter. The air flow rate can be continuously controlled if multiple orifices and multiple particles are available and if the opening conditions of each orifice can be individually set.

Next, the opening condition of the orifice is detailed. The condition for the vibration to open an orifice is as follows [18]. Let m be the mass of a particle, P be the air pressure, and r be the radius of an orifice. The force F_1 at which the particle is pressed onto the opening of the orifice is expressed as follows:

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

The force F_2 that the vibration of the orifice plate applies to the particle can be expressed as:

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

where A is the vibration amplitude and ω is the angular velocity. The particle leaves the orifice opening when F_2 exceeds F_1. From the above condition, the condition for the vibration acceleration a of the orifice plate in which the particle moves away from the orifice opening can be expressed as follows:

$$a > \frac{\pi r^2 P \pm mg}{m} \quad \ldots \ldots \ldots \ldots \quad (3)$$

where $a = A\omega^2$. The above results confirmed that the flow rate could be controlled by controlling the applied voltage to the PZT and by adjusting the vibration amplitude of the orifice plate.

In a previous study, primary flexural vibration was generated on an orifice plate and the orifice vibration amplitude was changed by adjusting the position of the orifice to realize continuous flow control [19].

2.2. Novel Working Condition

It is necessary for the orifice opening conditions to be largely different depending on the orifices for the stabilization of flow characteristics. In Eq. (3), the orifice opening condition for a is dependent on the mass m. **Fig. 3** shows the necessary conditions for the particle diameter and the opening. In the figure, the applied air pressure is 0.5 MPa, the orifice diameter is 0.4 mm, and the particle material is SUS304 (density: 7.93×10^3 kg/m^3). It can be observed in **Fig. 3** that the vibration acceleration necessary to open an orifice largely changes with the change of the particle diameter. If particles of different diameters are confined in the control valve, particles of larger diameters would move away from the orifice as the vibration amplitude is gradually increased by changing the applied voltage. Consequently, a continuous flow rate control is realized. Additionally, as shown in **Fig. 3**, the change in the vibration acceleration is large when the particle diameter is small. If particles with a diameter of the above-mentioned scale are used, the opening conditions are largely different from each other depending on the orifice. Therefore, unintended opening or closing of the orifices during the operation of the control valve does not occur and the flow rate can be stabilized. Specifically, the proposed working principle can simultaneously realize continuous flow rate control and stable output at each flow rate. In this study, multiple particles of different di-

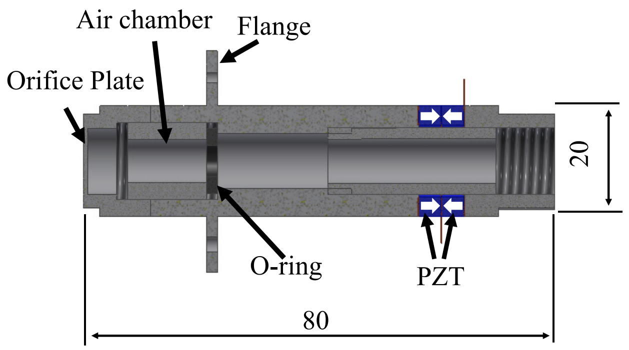


Fig. 4. Cross-section of the prototype.

ameters were used to realize flow control for stable output at an arbitrary flow rate.

3. Design of Prototype

A prototype was made to confirm the effectiveness of the proposed working principle. The conditions for the prototype to realize the control method proposed in this paper included the following:

- It should generate large vibration acceleration in a wide area.
- The difference in the vibration acceleration needed for particles to open the orifice is large.
- The vibration acceleration at each orifice is the same.

In this study, the vibration acceleration necessary to satisfy the proposed vibration conditions and open multiple orifices was generated. To prevent unintended opening or closing of the orifices, it is desirable that the opening conditions of the orifices are largely different from each other. Additionally, since it is not possible to forecast the orifice that will be closed with a particle when the control valve is driven, the vibration condition should be the same for all the orifices. The transducer structure, condition of the particles, and condition of the orifice position were all configured to satisfy the above requirements.

3.1. Structure of Vibration

A bolt-clamped Langevin transducer was used for the prototype valve to generate large vibration acceleration in a wide area. **Fig. 4** shows a cross-section of the manufactured control valve. The arrow on the PZT in the figure indicates the polarization direction. As in **Fig. 4**, the transducer is hollow with an orifice plate fixed at the tip. It was designed such that an antinode stays at the orifice plate and the nodes remain at the flange and PZT. The whole transducer expands and contracts in resonance driving. The displacement is magnified at the orifice plate, and causes a large vibration acceleration of the orifice plate. The transducer is fixed at the flange part. An air pressure application pipe is fixed through an O-ring to the inside of the flange. Therefore, the space extending from the O-ring to the orifice plate is an air chamber. A proportional

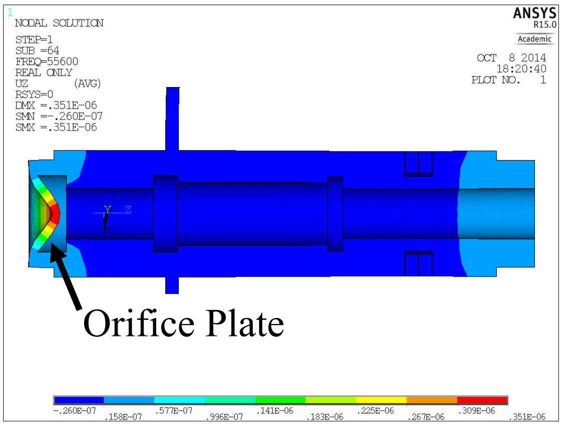


Fig. 5. Vibration mode of prototype.

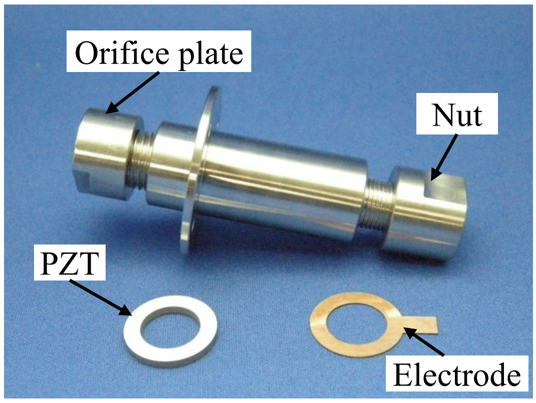


Fig. 6. Components of prototype.

control valve with a transducer that has a similar structure was also developed [20]. The total length of the transducer was 80 mm, and the diameter was 20 mm. The outer diameter of the orifice plate was 12 mm, and its thickness was 1.2 mm. **Fig. 5** shows vibration modes of the prototype valve calculated by the finite element method. It can be observed from the figure that the antinode was formed on the orifice plate and the node was formed on the flange. Additionally, the central part of the orifice plate was largely deformed. The components of the prototype are shown in **Fig. 6**. The transducer unit consisted of the orifice plate, transducer body, fixing nut, and orifice plate and the fixing nuts were connected to the body with dedicated bolts. The components of the transducer were made of stainless steel.

The dimensions of the PZT included an outer diameter of 20 mm, an inner diameter of 12 mm, and a thickness of 4 mm. The electrode was a 0.1 mm thick copper plate. The prototype weighed 150 g, and it was lighter than commercially available proportional control valves.

3.2. Condition of Particles

In this study, the opening condition was changed not by changing the material of particles but by changing the diameter of the particles. The diameter of the orifice was 0.4 mm and the applied air pressure was 0.5 MPa. Six different types of particles were chosen from **Fig. 3**. **Table 1**

Table 1. Specification of particles.

Diameter [mm]	Mass [$\times 10^{-7}$kg]	Acceleration [$\times 10^{4}$m/s^{2}]
0.5	0.52	12.1
0.6	0.90	7.01
0.7	1.42	4.41
0.8	2.13	2.96
1.0	4.15	1.51
1.2	7.17	0.88

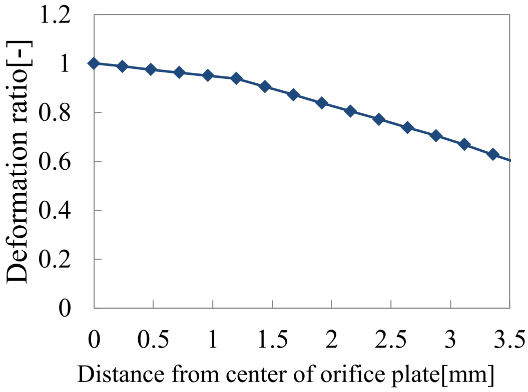
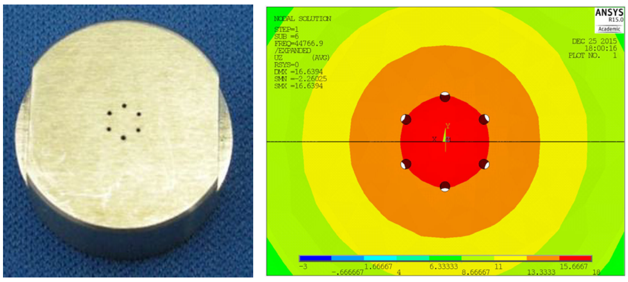


Fig. 7. Relationship between distance from center of orifice plate and deformation ratio.



(a) (b)

Fig. 8. Orifice plate.

shows their mass and vibration acceleration necessary to open the orifice. The particles of the diameters ranging from 0.5 mm to 1.0 mm were made of SUS304. The particles of diameter 1.2 mm were made of bearing steel SUJ2 (density: 7.86×10^3 kg/m^3). The study aimed for stable output through 6-step flow rates by using these particles.

3.3. Orifice Condition

Six orifices were placed at constant intervals on a circle centered at the center of the orifice plate so that the vibration acceleration at each orifice was the same. The distribution of the vibration amplitudes calculated by the finite element method is shown in **Fig. 7**. In the vibration mode used in this paper, the vibration amplitude was large at the center of the orifice plate and small at the plate edge. The positions of multiple orifices placed on a plate should be away from the center to prevent interference among the particles. However, the vibration amplitudes at the positions away from the center were not sufficiently large. Therefore, by considering the balance between the vibration amplitude and the interference of the particles, all the orifices were placed on a 1.5 mm radius circle whose center was located at the plate center. **Fig. 7** indicates that the vibration acceleration at a position 1.5 mm from the center is approximately 90% of the vibration acceleration at the center. **Fig. 8(a)** shows a photograph of the orifice plate, and **Fig. 8(b)** shows the vibration shape of the orifice plate calculated by the finite element method. It can be observed from **Fig. 8(b)** that the vibration amplitude was the same at every orifice position.

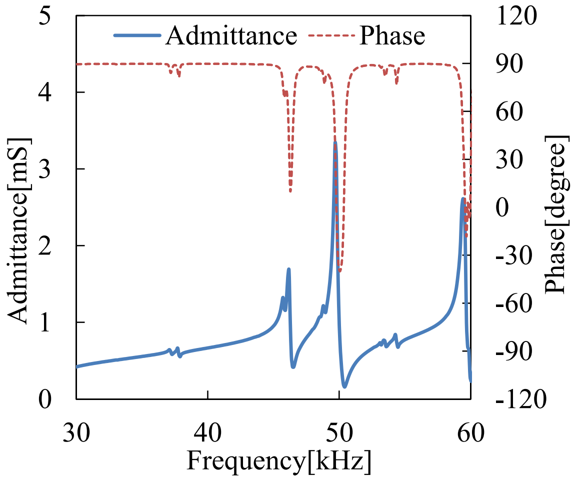


Fig. 9. Relationship between admittance of the prototype and frequency.

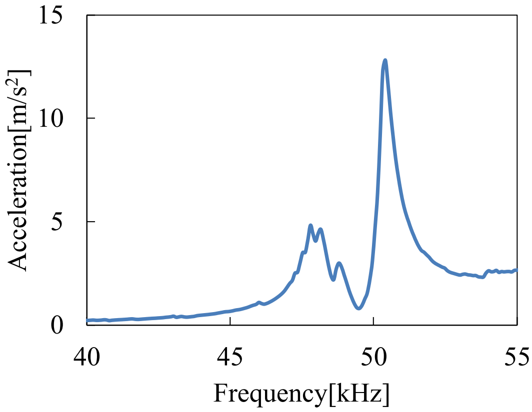


Fig. 10. Relationship between prototype acceleration and frequency.

4. Basic Characteristics of Prototype

4.1. Vibration Characteristics

The characteristics of the designed transducer were examined. **Fig. 9** shows the admittance and phase as functions of the frequency. It can be observed from the figure that the admittance and phase changed notably at approximately 50 kHz. Next, the vibration acceleration at the center of the orifice plate was measured with a laser

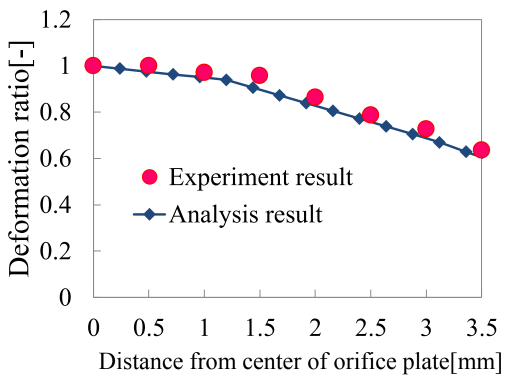


Fig. 11. Relationship between distance from center of orifice plate and deformation ratio.

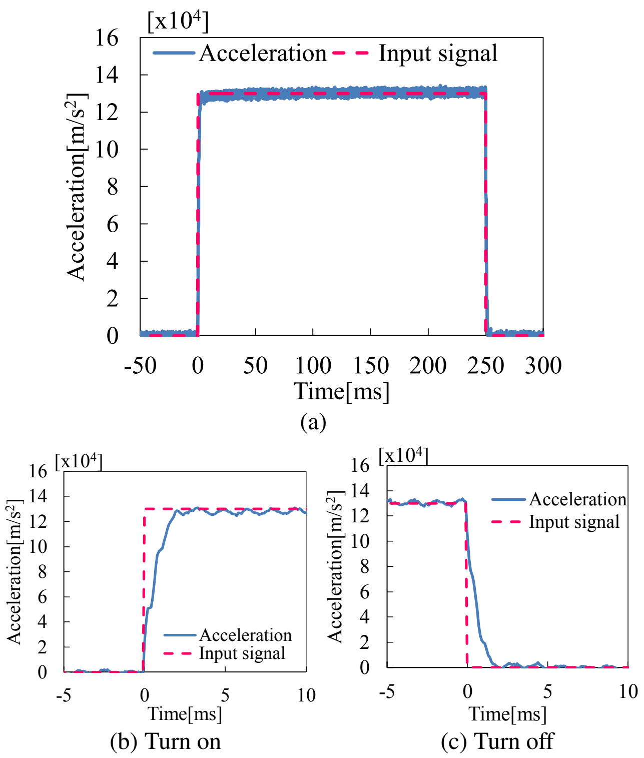


Fig. 12. Response of the transducer.

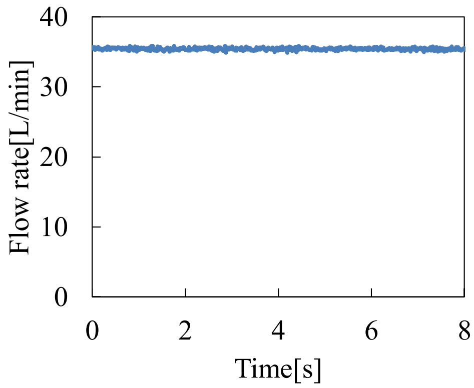


Fig. 13. Maximum outlet flow rate of prototype.

Doppler vibrometer. The applied voltage was 10 V_{p-p}. The measurement results are presented in **Fig. 10**. As indicated by the results, the orifice plate was deformed notably at 50 kHz. With the frequency fixed to 50 kHz and applied voltage to 10 V_{p-p}, the deformation ratio of the orifice plate was obtained by measuring the vibration acceleration at positions in the direction from the center of the orifice plate at intervals of 0.5 mm. The deformation ratio obtained from the experiment and that from the analysis are illustrated in **Fig. 11**. The figure shows that the deformation ratio of the orifice plate obtained from the experiment is in good agreement with that from the analysis. The above results indicate that the vibration mode of 50 kHz was the result expected in the analysis.

Next, the responsiveness of the transducer resonating at 50 kHz was measured. The responsiveness was obtained by measuring the vibration of the orifice plate by a laser Doppler vibrometer at stepwise switching of the input voltage of the resonant frequency. Every signal was filtered to extract effective values to facilitate easy comparison between the input voltage and the vibration acceleration. The experiment results are shown in **Fig. 12**. **Fig. 12(a)** shows that the acceleration of the transducer follows the input voltage. **Figs. 12(b)** and **(c)** show the magnified views of the turn-on and turn-off points of the results. The acceleration at either the turn-on or turn-off point follows the input voltage within approximately 3 ms. The above results suggest high responsiveness of the developed control valve.

4.2. Flow Characteristics

The basic flow characteristics of the developed valve were examined. First, the maximum flow rate and the flow rate per orifice were measured. The flow characteristics under an air pressure of 0.5 MPa with no particles confined in the control valve were measured with a thermal flow meter. The experiment results are given in **Fig. 13**, which indicates that the maximum flow rate at 0.5 MPa is 35 L/min and the flow rate per orifice is approximately 5.9 L/min.

Next, the flow rate characteristics were measured while increasing the vibration acceleration of the transducer with confined particles. The experiment system is shown in **Fig. 14**. The experiment system consisted of a pneumatic system and driving system. The pneumatic system consisted of a compressor, an air pressure gauge, and a flow meter. The air pressure was set and maintained at 0.5 MPa. The air flowed through the flow meter into the control valve. Each of the particles described in **Table 1** was confined in the valve. The air flowing in the control valve was discharged to the outside of the valve. The driving system consisted of a function generator and voltage amplifier. In the experiment, the flow rate was measured by changing the voltage from 0 to 120 V_{p-p} at the resonance frequency of 50 kHz for the control valve with the particles confined. Simultaneously, the vibration acceleration at the orifice position 1.5 mm from the center of the orifice plate was measured with the laser Doppler vibrometer. Only effective values were collected through a lock-in amplifier from the laser waveforms.

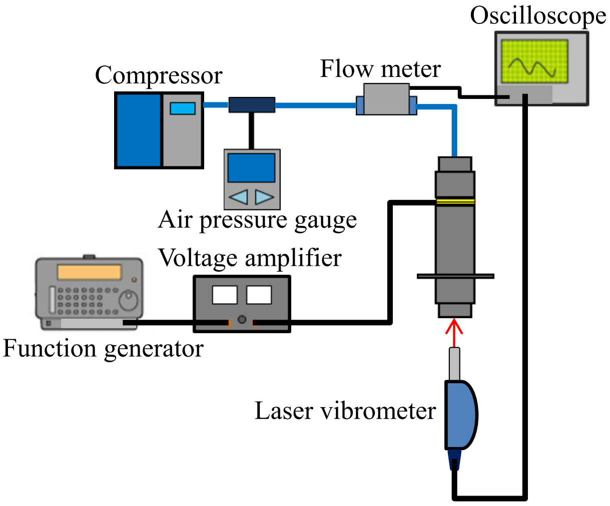


Fig. 14. Experimental setup.

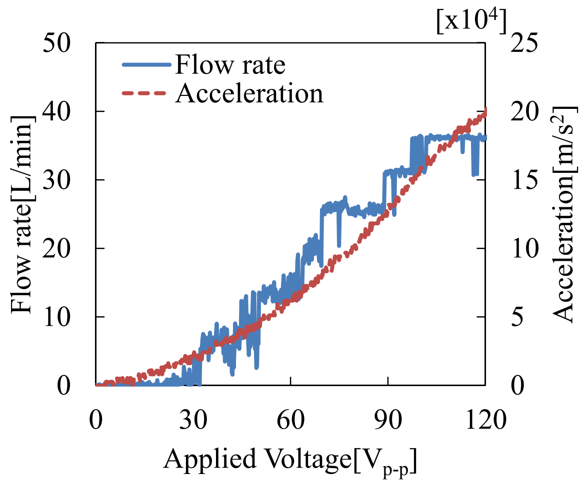


Fig. 15. Relationship between flow rate, acceleration, and applied voltage.

The experiment results are given in **Fig. 15**. The results show that the flow rate increases stepwise with increasing applied voltage. This is because the number of the orifice openings increases with increasing vibration acceleration. Conversely, the flow characteristics are unstable when the flow rate is low. It was also revealed that the flow rate becomes unstable immediately after the flow rate increases. This result could be because the vibration condition was not stable when the orifice opening condition was about to be satisfied.

5. Stable Flow Experiment

Based on the experiment results presented in the previous section, the vibration acceleration required to open each orifice in a stable way was determined. The flow characteristics were measured at constant vibration acceleration. The determined vibration acceleration of the orifices is shown in **Table 2**. The experiment system shown previously was used to measure the flow rate and the vibration acceleration of the orifice plate under the conditions listed in **Table 2**. The experiment results are shown in **Fig. 16**. The figure indicates that the vibration acceleration was constant as long as the applied voltage was kept constant. Additionally, it was observed that the flow rate is stable if the vibration acceleration is constant. Conversely, in **Figs. 16(c)**, **(e)** and **(f)** there is a temporal decrease in the flow rate. This was because the particles could move away from an orifice opening to another open orifice, and close the opening, resulting in a decrease of the flow rate. As shown in **Fig. 16(c)**, this phenomenon occurred drastically and the flow rate decreased for approximately 2 s. The experiment shown in **Fig. 16(c)** was conducted with 0.8 mm particles, and the particles proba-

Table 2. Stable driving conditions.

Diameter [mm]	Acceleration [$\times 10^4$m/s^2]
0.5	16.8
0.6	11.1
0.7	9.0
0.8	6.9
1.0	5.0
1.2	2.7

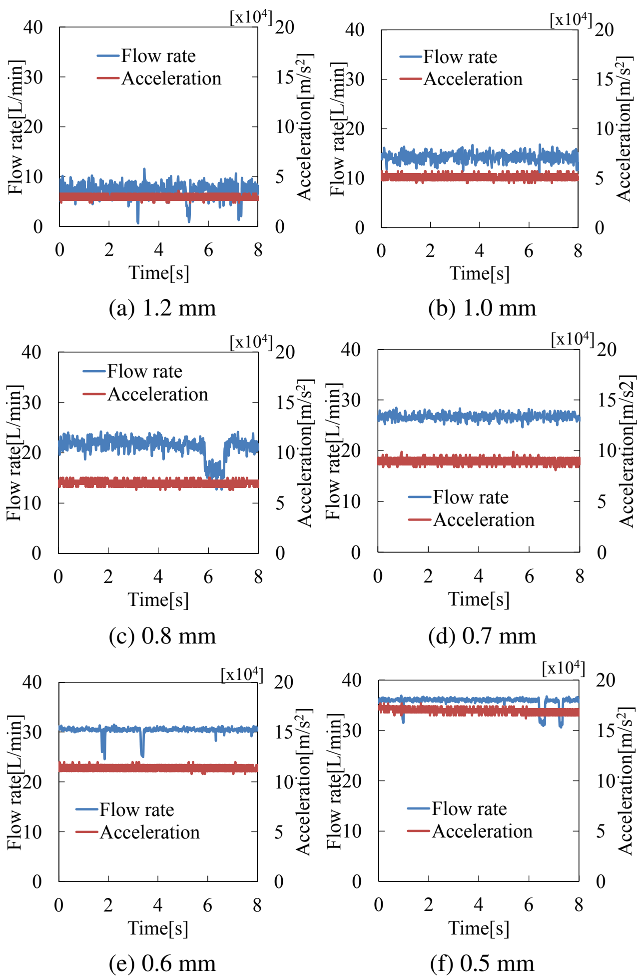


Fig. 16. Static flow rate characteristics.

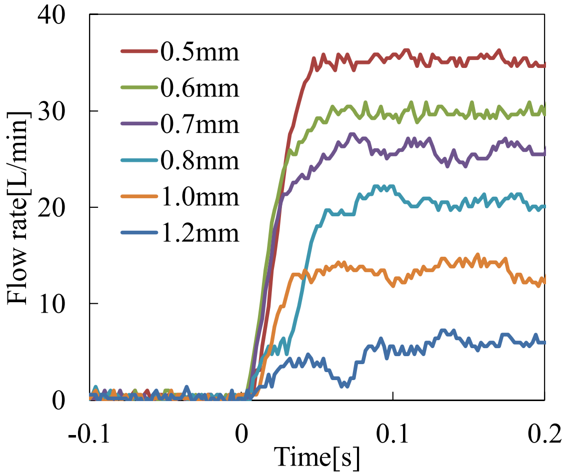


Fig. 17. Response of flow conditions.

bly remained at the orifices for a relatively long time because of the small difference between the preset working condition and the opening condition of the orifice. In contrast, no increase in the flow rate was observed in any other experiment results. The effectiveness of the method of changing the opening condition of the orifice by using particles of different masses was confirmed from these results. Finally, the start-up behavior of the flow rate was examined under the condition that a stable flow rate could be maintained. The result is shown in **Fig. 17**. It can be observed from the figure that for all particle sizes, the flow rate begins increasing immediately after the voltage is applied and it reaches the target rate in approximately 50 ms. It takes more time for the flow rate to stabilize for 0.8 mm particles. As in the preceding experiment, this could be due to the small difference between the preset condition and the opening condition of the orifice. It was therefore confirmed that the present control method could realize stable start-up behavior of the flow rate. Conversely, the particles did not close the orifices and the air flow was not stopped in the turn-down behavior of the particles. This could be because the orifice plate area was much larger than the orifice diameter. Furthermore, the particles stayed at positions where the particles were not influenced by the air flow. Optimizing the diameter of the orifices and the area of the orifice plate could solve this problem.

6. Conclusion

In this study, a flow rate control device working under a new working principle for stable output of continuous flow was developed. The developed control uses a PZT whose vibration excites and opens fine particles on orifices. A new valve control mechanism was proposed, in which fine particles of different masses are used to create a difference in the orifice opening conditions for stable flow output with continuous flow rate characteristics. A prototype was built with a bolt-clamped Langevin transducer, and flow output at 6-step flow rates was successfully realized using six types of fine particles. Also, stable output at an arbitrary flow rate was realized by driving the transducer at a constant voltage. High responsiveness was observed in the start-up behavior. In comparison, the flow behavior became unstable and the responsiveness became slower when the working conditions were not optimal. Optimizing the orifice diameter and fine particle conditions to extend the stable flow range could circumvent these phenomena. Additionally, there was a problem in the flow responsiveness in the turn-down behavior. This was because the orifice plate (ϕ 12 mm) was significantly larger than the orifice diameter (ϕ 0.4 mm). Optimizing the orifice diameter and orifice plate shape by using a smaller air chamber and restricting the motion area of the fine particles could solve this problem. This topic will be explored in a future study.

Acknowledgements

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