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Hydraulic Control by Flow Control Valve Using Particle Excitation

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In this paper, we report on the hydraulic characteristics of a particle-excitation control valve, which was originally developed for flow rate control in pneumatic actuators. The orifices are opened and closed with particles excited by the vibration of the orifice plate and the fluid force. This results in a more simple and compact structure, and higher flow rate-to-weight ratio than in conventional pneumatic valves. Because the traditional hydraulic valves are bulky and heavy, the purpose of this study is the development of a small and lightweight hydraulic valve by applying the working principle of the particle-excitation valve to hydraulics. We have focused on two characteristics affected by changing the working fluid from air to oil. One is the vibration of the orifice plate and the other is the movement of the particles. As a result, it is found that the inertia of the working fluid reduces the vibrational velocity of the orifice plate by 24%, whereas the viscosity of the working fluid raises the required operating voltage of the valve by 167% because of its influence on the movement of particles. In addition, when silicone oils are used as the working fluid, with kinematic viscosity values of 1 mm^2/s, 2 mm^2/s, and 3 mm^2/s, the maximum volumetric flow rates of the prototype valve are 891 ml/min, 887 ml/min, and 838 ml/min, respectively. These experimental results demonstrate the potential of the proposed valve for hydraulics.

Keywords: Proportional Control Valve, Hydraulics, Flow Control, Piezoelectric Element, Micro-Mechanism

1. Introduction

Compared to robots equipped with electromagnetic actuators, “tough” robots made with hydraulic actuators, represented by the BigDog robot, may be capable of surviving severe external impacts and producing large amounts of force[1)-3)]. However, despite having these benefits, hydraulic-actuator robots require the mounting of multiple hydraulic servo valves in order to perform multi-degree-of-freedom motions like those achieved by electromagnetic-actuator robots.

The miniature hydraulic servo valves used in aircrafts, for example, are suitable for robots in terms of size and weight. However, such servo valves are high in cost and pose a problem for the development of hydraulic robots with multiple degrees of freedom. Therefore, the objective of this study is the development of a low-cost miniature hydraulic servo valve, of simple construction and mountable size, for hydraulic robots.

Some of us previously developed a flow control valve for pneumatic use[4)-7)]. This flow control valve excites minute particles in a flow path with piezoelectric elements, thereby opening and closing orifices to control the flow. This allows for a simple miniature structure that achieves a high mass-flow ratio compared to common pneumatic flow control valves. The application of the working principle of this flow control valve is expected to lead to the development of a less expensive, miniature, and lightweight hydraulic servo valve. However, this pneumatic control valve cannot simply be operated by applying the previous design techniques to oil control. The reason for this is that changes in the physical properties of the working fluid, such as an increase in the viscous resistance acting upon the inertia of the minute particles in the working fluid, may inhibit the movement of the control valve.

In this study, we focused on the vibrational velocity of the orifice plate and the fluid resistance experienced by the minute particles in the working fluid, as the elements affected by the density and viscosity of the working fluid, and then identified the effects of these fluid properties from numerical analyses and experiments. In addition, we performed operational experiments on a prototype flow control valve using silicone oils of different kinematic viscosities as working fluid, thereby identifying its operating conditions and characteristics.

2. Nomenclature

F_D	:	Resistance experienced by minute particles from working fluid
F_I	:	Minute particle inertia force
F_P	:	Pressing force on orifices from minute particles due to pressure
P	:	Supply pressure (gauge pressure)
μ	:	Working fluid dynamic viscosity
ν	:	Working fluid kinematic viscosity
ρ	:	Working fluid density

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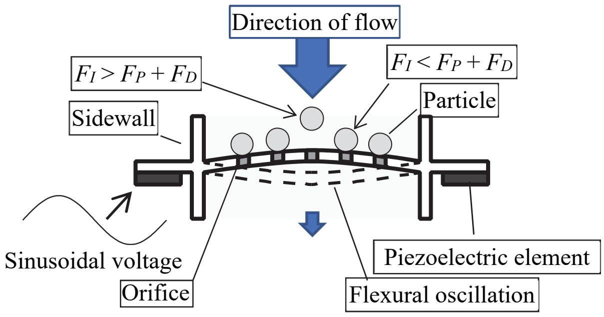


Fig. 1 Working principle of the valve using particle excitation.

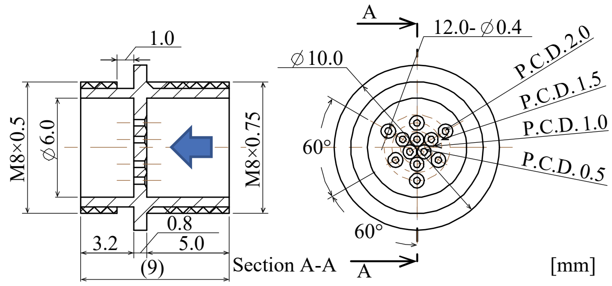


Fig. 2 Schematics of the orifice plate. The arrow in left figure indicates the direction of flow.

Table 1 Silicone oils used in this study[8].

No.	ν [mm^2/s]	μ [× 10^{-6} Pa·s]	ρ [kg/m^3]	Speed of sound [m/s]
#1	1	818	818	901.3
#2	2	1700	850	-
#3	3	2610	869	-
#4	4	3540	884	-
#5	5	4480	897	-
#6	10	9350	935	966.5
#7	30	28700	955	-

Table 2 Specifications of the flow control valve.

Item	Value
Diameter [mm]	10.0
Height [mm]	9.0
Weight [g]	2.5
Number of orifices	12
Orifice diameter [mm]	0.4
Number of particles	12
Particle diameter [mm]	0.8

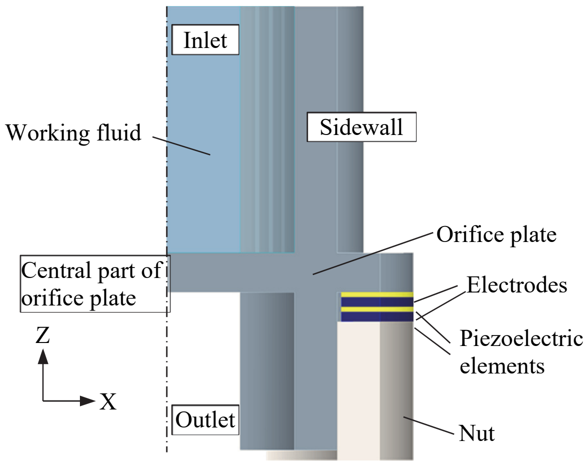


Fig. 3 Quarter model of the valve for FEM analysis.

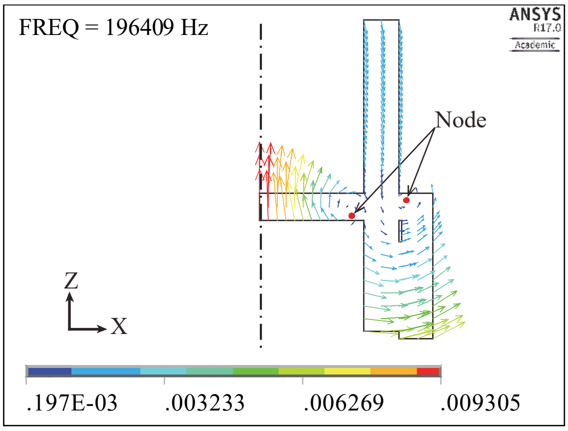
3. Structure of particle excitation flow control valve

Figure 1 shows the working principle of a particle-excitation flow control valve[4]. This flow control valve consists of the orifice plate, upon which multiple orifices have been arranged; minute particles; and piezoelectric elements. When this valve is not in operation, the pressure of the working fluid presses the minute particles against the orifices, stopping the flow of fluid. Fluid flows when these minute particles are separated from the orifices, and by controlling the number of minute particles, it is possible to change the flow rate. When the orifice plate is resonated by the piezoelectric elements, the minute particles leap from the orifice plate with their own inertia force, resulting in the opening of the orifices. In order to separate the minute particles from the orifice plate, the inertia force must exceed the pressing force from fluid pressure and the resistance from the viscosity and inertia of the working fluid.

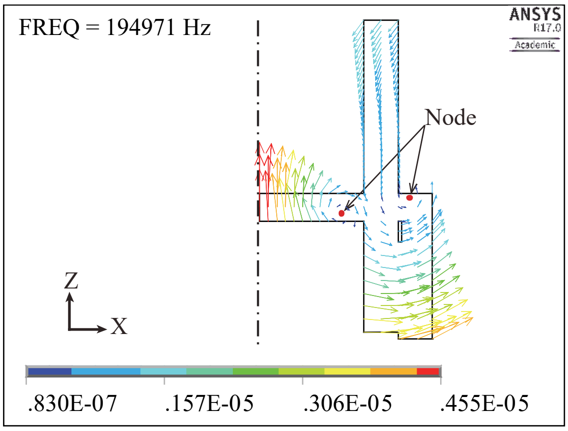
When common ISO VG32 hydraulic oil and air are compared, the dynamic viscosity of the oil is approximately 1:1500 that of air, and its density is approximately 1:700. In order to achieve hydraulic control, their effects upon the movement of a control valve needs to be identified. Therefore, in this study, we used seven types of silicone oil with different kinematic viscosities, as shown in Table 1, and verified their effects. Note that types #2 to #5 shown in Table 1 are generated by #1 and #6 silicone oil mixture ratios.

The main specifications and shape of the orifice plate used for the flow control valve in the experiments here are shown in Fig. 2 and Table 2, respectively. The dimensions of the flow control valve are as follows: outer diameter 10 mm, height 9 mm, and mass 2.5 g. SUS-304 and 0.2-mm-thick ring-shaped lead zirconate titanate (PZT) are used for the structural materials and the piezoelectric elements that drive them, respectively.

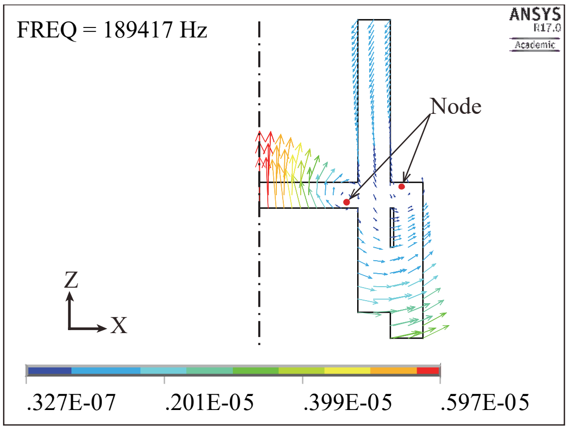
The piezoelectric elements are in a multi-layer configuration and secured to the orifice plate with nuts. A previous and proven design of a pneumatic control valve was used for determining the arrangement and diameter of the orifices[5)-7)].



(a) Working fluid: Air, Number of PZT: 2



(b) Working fluid: #1, Number of PZT: 2



(c) Working fluid: #1, Number of PZT: 4

Fig. 4 Analytical results of vibrational mode, for three typical conditions.

4. Orifice plate vibration characteristics

In this section, we describe the effects of various operating conditions on the vibration characteristics of the orifice plate, focusing mainly on the change of the working fluid, from air to oil.

4.1 Modal analysis by finite element method

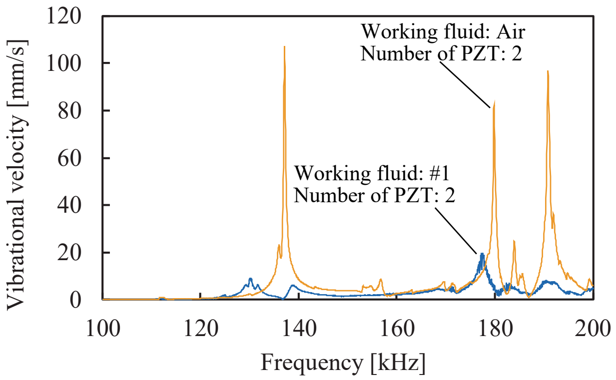
This flow control valve is actuated by resonating the orifice plate in a deflecting direction, which generates inertia force in the minute particles, causing them to separate from the orifices. Thus, when the working fluid is oil, larger vibration energy is required than in pneumatic situations owing to the density and viscosity of oil. Furthermore, this larger vibration energy requires a greater number of piezoelectric element layers, which generally leads to a decreased control valve resonant frequency. Therefore, through a modal analysis, we identified the effects of the working fluid inertia and the number of piezoelectric elements on the resonant frequency and the mode shape. To accomplish this, we used the ANSYS finite element analysis software. We focused on the inertial force of fluid, which is believed to have the greatest effect upon resonant frequency, and did not consider the applied pressure and working fluid viscosity.

Figure 3 shows a quarter model of the valve used for the analysis. We modeled the working fluid as an acoustic fluid element, and then divided the entire mesh into hexahedrons with 20 nodes. The boundary conditions considered the X-Z and Y-Z planes as symmetrical. In the model with a two-layer piezoelectric element configuration, the number of nodes was 21517, whereas in the model with a four-layer piezoelectric element configuration, the number of nodes was 22032. The corresponding material properties of air and #1 silicone oil were provided as acoustic fluid elements, i.e., speed of sound and density.

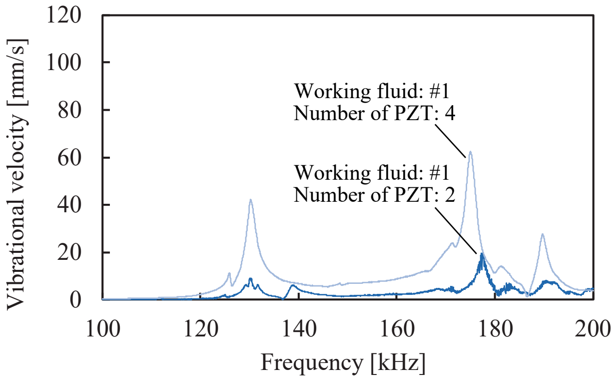
Based on the analysis of the modes, Figure 4 shows the displacement vectors of the nodes on the plane X-Z, with the central part of the orifice plate resonating greatly in a deflecting direction. The resonance mode is rotating around two nodes, the resonant frequency of which decreases 1.4 KHz when changing the working fluid from air to oil (comparison of Figs. 4(a) and (b)), and decreases 5.6 kHz as a result of changing the number of piezoelectric element layers from two to four (comparison of Figs. 4(b) and (c)). This result shows that the variation in resonant frequency caused by changes in the working fluid and in the number of piezoelectric element layers is 3% or less. Thus, the effect of these changes on the vibrational mode and resonant frequency is confirmed to be small.

Table 3 Experimental conditions.

Item	Value
Working fluid	Air, Silicone oil
Applied pressure [MPa]	0.1, 0.3, 0.5
Driving voltage [$V_{p\text{-}p}$]	10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Kinematic viscosity of silicone oil [mm^2/s]	1, 10, 30
Number of piezoelectric elements	2, 4
Fluid temperature	Ambient temperature (18 ± 2°C)



(a) Influence of the working fluid.



(b) Influence of the number of PZT.

Fig. 5 Vibrational velocity at the central part of the orifice plate vs. driving frequency.

4.2 Analysis of vibration characteristics through experiments

Through experiments, we vibrated the orifice plate under multiple conditions and identified the effects of these conditions on the vibration characteristics. Table 3 shows the experimental conditions. In order to confirm the vibration states, we used a laser Doppler vibrometer (Polytech OFV-3001) and a frequency response analyzer (NF FRA-5095), and measured the vibrational velocity in the central part of the orifice plate (center of right-side figure in Fig. 2). We made a prototype control valve with no orifices in order to conduct experiments applying constant pressure, and fixed it to an aluminum block. Furthermore, in order to reduce the variations in the constraint state, we arranged a cushioning material between the aluminum block and fixtures. We will describe the effects of the different conditions on the vibration characteristics in the sections i) to v) below.

i) Effects of working fluid viscosity and density

Figure 5(a) shows the measurement results from frequency responses using air or #1 silicone oil as the working fluid. The measurement conditions were as follows: applied voltage 10 $V_{p\text{-}p}$, applied pressure 0.5 MPa, and a two-layer piezoelectric element configuration. The measured frequency domain was 100 kHz to 200 kHz, which is presumably the domain in which the resonance points are present, according to the results of the modal analysis. In the results from the measurements using air as the working fluid, notably large amplitude was measured at three frequencies: 137.1 kHz, 179.8 kHz, and 190.8 kHz. As shown in the above modal analysis, the resonance points do not shift more than 1% by changing the working fluid. These results indicate that the resonance mode at 130.2 kHz, 177.3 kHz, and 190.5 kHz when silicone oil is used, corresponds to those at 137.1 kHz, 179.8 kHz, and 190.8 kHz when air is used. Therefore, regarding the use of silicone oil, when we compare its maximum vibrational velocity at a resonance point corresponding to that of air, the resonance points at 130.2 kHz and 190.5 kHz showed a 90% or more decrease in vibrational velocity. Table 4 shows the comparison results for the resonance point at approximately 177.3 kHz, which had the smallest attenuation. By changing the working fluid from air to silicone oil, it is reduced the vibrational velocity and Q factor in 76% and 72%, respectively. Moreover, the resonant frequency decreased 2.5 kHz.

ii) Effect of number of piezoelectric element layers

We changed the number of piezoelectric element layers from the conditions in which silicone oil was used in section i) to four layers, and then considered the effects. Figure 5(b) shows the measurement results for frequency response. Large amplitude was measured at three frequencies: 130.3 kHz, 175.1 kHz, and 189.7 kHz. Based on the results of the modal analysis, the effect on resonant frequency of the number of piezoelectric element layers was 3% or less, and thus, the resonance point at 175.1 kHz, which had the largest vibrational velocity, is thought to have had the same resonance mode as the two piezoelectric elements resonance point at 177.3 kHz. Therefore, Table 4 shows the results of comparing both. Although changing the number of piezoelectric element layers from two to four raised the vibrational velocity 217%, the Q factor decreased by 25%. In addition, the resonant frequency decreased in 2.2 kHz.

Table 4 Measurement results of resonant frequency, vibrational velocity, and quality factor in each setup.

Setups			
Working fluid	Air	Silicone oil: #1 in Table 1	
Number of piezoelectric elements	2	2	4
Results			
Resonant frequency [kHz]	179.8	177.3	175.1
Vibrational velocity [mm/s]	82.2	19.7	62.4
Quality factor	244	69	52

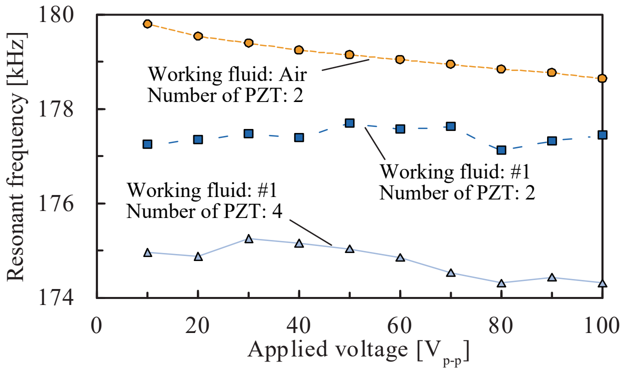


Fig. 6 Relationship between resonant frequency and applied voltage.

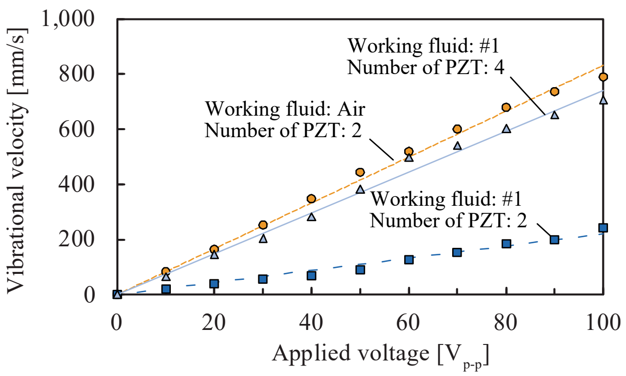


Fig. 7 Relationship between vibrational velocity at the central part of the orifice plate and the applied voltage.

In the measurements below, we will describe the results involving the resonant frequency shown in Table 4.

iii) Effect of applied voltage

Regarding the three conditions shown in Table 4, Figs. 6 and 7 show the relationships of applied voltage with resonant frequency and vibrational velocity. When air was used as the working fluid, the resonant frequency decreased with increased applied voltage, and comparing the cases of 10 $V_{p\text{-}p}$ and 100 $V_{p\text{-}p}$ applied voltage shows a decrease of 1.2 kHz. In addition, when silicone oil was used as the working fluid, regardless of the number of piezoelectric elements, the resonant frequency moved upward and downward with the increasing applied voltage, with a maximum difference of 0.9 kHz. The relationship of applied voltage and vibrational velocity was linear for all conditions.

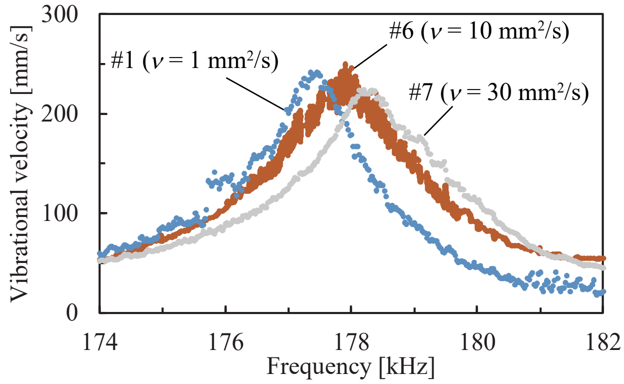


Fig. 8 Relationship between vibrational velocity, kinematic viscosity, and driving frequency around resonant frequency.

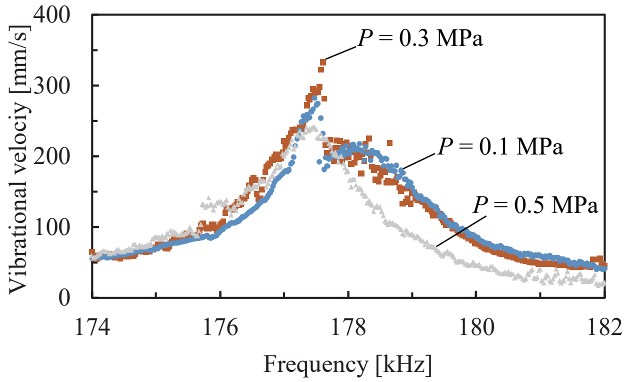


Fig. 9 Relationship between vibrational velocity, applied pressure, and driving frequency around resonant frequency.

iv) Effect of kinematic viscosity

We examined the effects of the working fluid on kinematic viscosity, using #1, #6, and #7 silicone oil. Figure 8 shows the measurement results for frequency response. We applied a voltage of 100 $V_{p\text{-}p}$ and a pressure of 0.5 MPa, and used a two-layer piezoelectric element configuration. Based on the results of the measurements, the increased kinematic viscosity caused the resonant frequency to rise, and when kinematic viscosity was increased from 1 mm^2/s to 30 mm^2/s, the resonant frequency rose by 0.7 kHz. On the other hand, when the kinematic viscosity was 10 mm^2/s and 30 mm^2/s, the vibrational velocity and the Q factor assumed a maximum and minimum value, respectively. The difference between maximum and minimum values was 10% for the vibrational velocity and 15% for the Q factor.

v) Effect of applied pressure

Figure 9 shows the measurement results for frequency response when the working fluid pressure was changed. The measurement conditions were as follows: #1 silicone oil for the working fluid, an applied voltage of 100 $V_{p\text{-}p}$, and a two-layer piezoelectric element configuration. Based on the measurement results, the change in resonant frequency was 100 Hz or less, and the relationship between applied pressure and vibrational velocity was not consistent. When the applied pressures were 0.3 MPa and

0.5 MPa, the vibrational velocity assumed maximum and minimum values, respectively, with a difference of 19% between them.

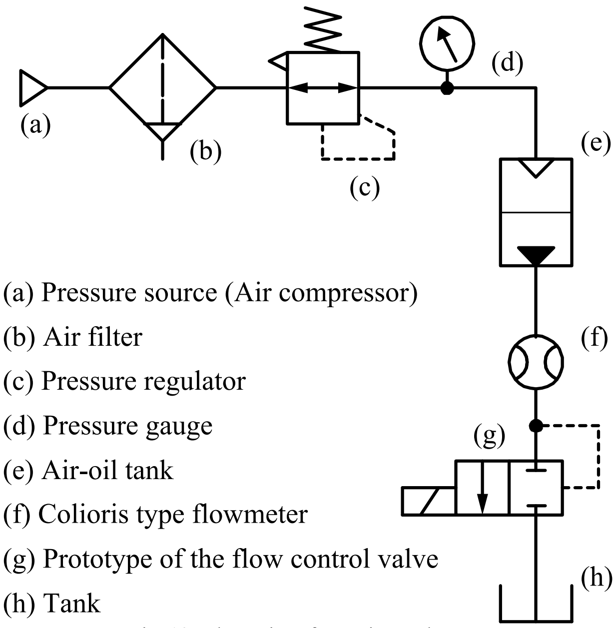


Fig. 10 Schematics of experimental setup.

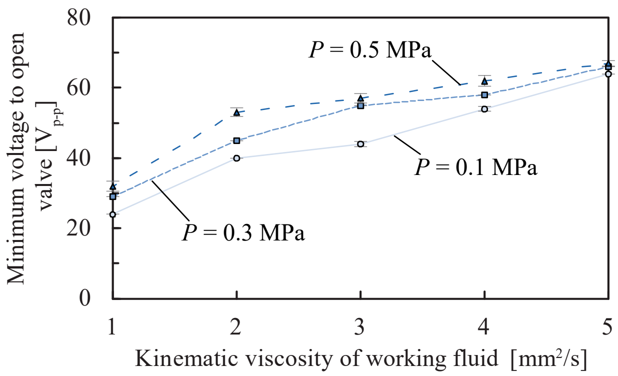


Fig. 11 Relationship between minimum voltage to open valve, applied pressure, and kinematic viscosity of the working fluid. Error bars show standard deviation.

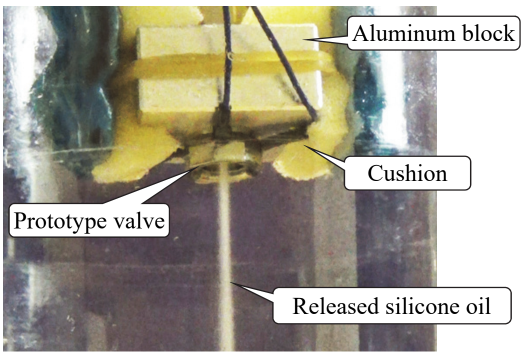


Fig. 12 Driving state of the prototype valve.

5. Behavior analysis of minute particles according to experiments

When the minute particles leap from the orifice plate, they experience pressing force from the fluid and resistance from the viscosity and inertia of the working fluid. When we measure the relationship between the applied voltage at which the orifices of the flow control valve open, the working fluid kinematic viscosity, and the applied pressure, we shall identify the effects of force on the minute particles from the increased viscosity and pressure of the working fluid.

Figure 10 shows the hydraulic circuit used in the experiments. We fixed the flow control valve to an aluminum block as the previous section. Because the two-layer piezoelectric element configuration of the flow control valve would not operate under all conditions, we used a control valve with a four-layer piezoelectric element configuration in the following experiments. In addition, the temperature of the silicone oil was 25°C that is the temperature at which is defined the kinematic viscosity. Based on driving frequency adjustments within a range of 170 kHz to 190 kHz, the frequency that worked the most often was 180 kHz. This frequency has a numerical value 5 kHz higher than the resonant frequency shown in section 4.2. The cause is thought to be the effect of whether orifices are present.

We used #1 to #5 silicone oils as the working fluid. Figure 11 shows the applied voltages at which the orifices would open. The applied pressures were 0.1 MPa, 0.3 MPa, and 0.5 MPa. The vertical axis shows the minimum voltage required to open the valve. We defined that the control valve stably opens, when the flow rate exceeded 5 ml/min. Based on the experimental results, the minimum voltage increased with increased kinematic viscosity and applied voltage, and the minimum and maximum values for the minimum voltage were 24 $V_{p\text{-}p}$ and 67 $V_{p\text{-}p}$, respectively. Figure 12 shows the driving state.

When the applied pressure was 0.1 MPa, and kinematic viscosity increased from 1 mm^2/s to 5 mm^2/s, the minimum voltage required to open the orifices increased by 167%.

As shown in section 4.2, we found that the applied voltage and vibrational velocity of the orifice plate are linear, and the effect of the working fluid pressure and viscosity on the orifice plate vibrational velocity is small. Consequently, as seen in Fig. 11, increases in the minimum voltage owing to increased hydraulic fluid pressure and kinematic viscosity are not caused by a decreased orifice-plate vibrational velocity. It is thought that they may be caused by the obstructed movement of the minute particles owing to the forces received from the hydraulic fluid, which are the force pressing the minute particles on the orifices by hydraulic pressure, as well as the resistance due to hydraulic fluid inertia and viscosity.

6. Experiments to evaluate flow characteristics

We measured the flow characteristics of the control valve in response to the applied voltage. The experiments were conducted in the same experimental system as in section 5. In addition, we used #1 to #3 silicone oils at a temperature of 25°C as the working fluid, within an applied pressure range of 0.1 MPa to 0.5 MPa. Figure 13 shows the experimental results.

The flow rate rose with increased applied pressure and applied voltage. When the applied pressure was 0.5 MPa, and the applied voltage was 140 $V_{p\text{-}p}$, the maximum flow rates for each fluid were 891 ml/min (#1, ν=1 mm^2/s), 887 ml/min (#2, ν=2 mm^2/s), and 838 ml/min (#3, ν=3 mm^2/s), respectively.

Figure 14 shows the relationship of kinematic viscosity, applied pressure, and maximum flow rate. When the kinematic viscosity was increased from 1 mm^2/s to 2 mm^2/s, and from 2 mm^2/s to 3 mm^2/s, for each applied pressure, the maximum flow rates decreased by a maximum of 1.4% and 6.1%, respectively.

As shown in Fig. 13, the following three stages were found regarding the variations of flow rate caused by a rising applied voltage.

At the first stage, when the relative applied voltage was low, the percentage of change in flow rate from voltage variations was small. This prominently appeared when the hydraulic fluid viscosity was high, with a high applied pressure. At this stage, the minute particles are thought to be near the orifices and repeatedly opening and closing them, in sequence. When the vibrational velocity of the orifice plate is small, the minute particles are pressed back against the orifices by the force from the working fluid immediately after leaping off. Then, because the particles remain near the orifices, the flow rate remains small. However, the flow rate is stable with fluctuations.

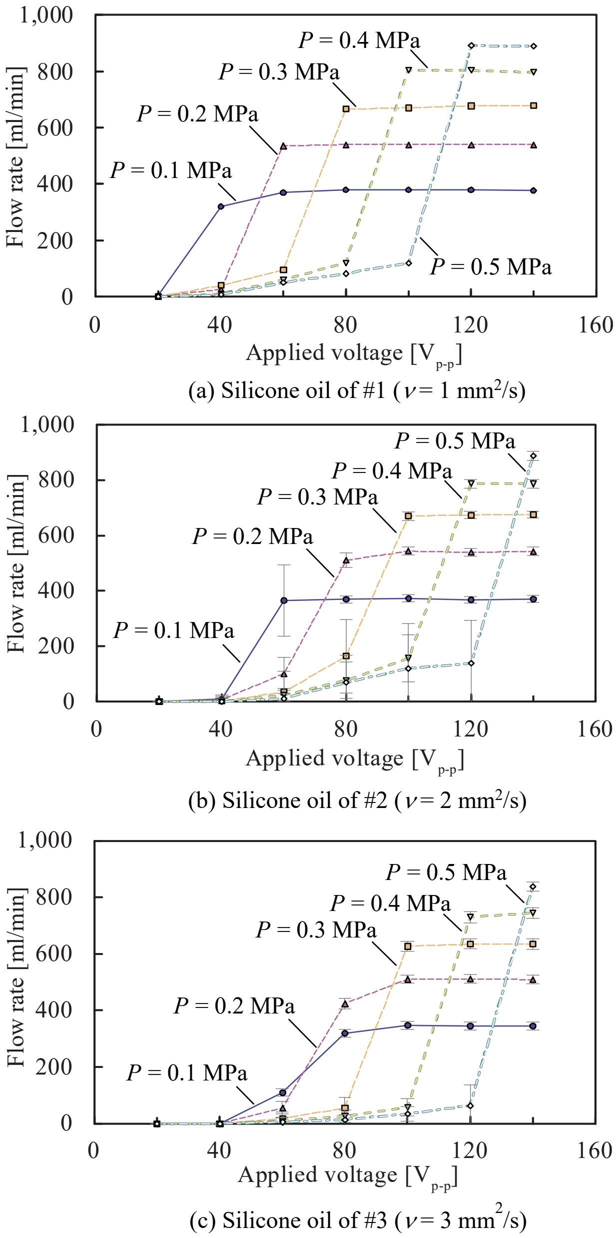


Fig. 13 Relationship between volumetric flow rate, applied pressure, and applied voltage. Error bars show standard deviation. Upper, middle, and lower figures show the results of different silicone oils (#1, #2, and #3 in Table 1, respectively).

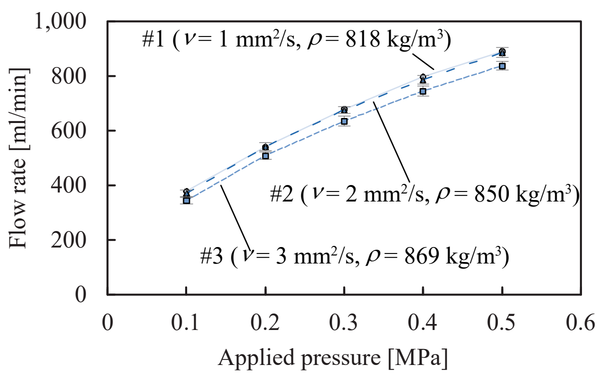


Fig. 14 Relationship between volumetric flow rate of the valve, kinematic viscosity, and applied pressure, when applied voltage was 140 $V_{p\text{-}p}$. Error bars show standard deviation.

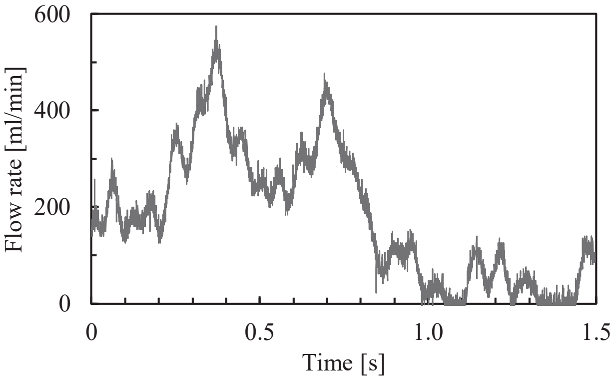


Fig. 15 Transition of flow rate, when the value of kinematic viscosity, applied pressure, and applied voltage were 2 mm^2/s, 0.3 MPa, and 80 $V_{p\text{-}p}$, respectively.

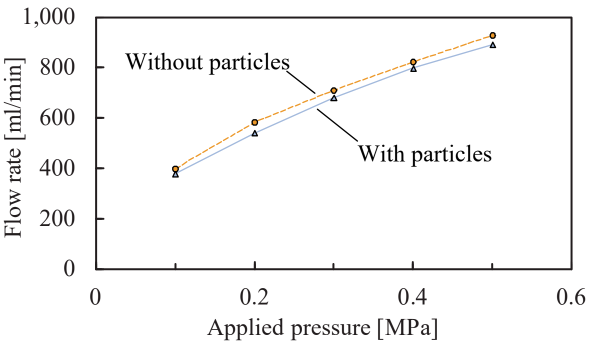


Fig. 16 Comparison between the flow rates with particles and without particles.

At the second stage, the flow rate rapidly transitions from low to high as the applied voltage rises. Within this domain, the flow rate is unstable, and it is difficult to stabilize and continuously control the flow rate against the applied pressure. Figure 15 shows changes in flow rate over time, with applied pressure of 0.3 MPa, applied voltage of 80 $V_{p\text{-}p}$, and with #2 silicone oil used as the working fluid. The mean flow rate was 164 ml/min, but the instantaneous flow rate within approximately one second changed greatly, between a maximum of 575 ml/min and a minimum of 0 ml/min. The cause of this is thought to be changes in the pressing force of minute particles because of pressure fluctuations within the control valve. When voltage is applied, initially the minute particles in the central part of the orifice plate fly off, but this results in the fluid within the control valve flowing out, which decreases the pressure within the valve. Decreased pressure within the control valve will decrease the pressing force upon the orifices from other minute particles, resulting in the particles leaping off from the orifices, and the instantaneous flow rate rising. On the other hand, an increased flow rate will increase the action of the minute particles pressing on the orifices. It is considered that with such a mechanism, the fluctuations in flow rate over time at this stage will be large, and the operation will be unstable.

At the third stage, the flow rate is saturated against rises in applied voltage. Figure 16 shows the experimental results from comparing flow characteristics without minute particles and the maximum flow rate with minute particles, when #1 silicone oil is used as the working fluid. The difference between the two is small. Flow rate is at maximum at the third stage. Therefore, it is found that at this stage, the minute particles are fully separated from the orifices, because of very strong particle excitation.

The voltage at which switching between these three stages occurs rises with the increased hydraulic fluid kinematic viscosity and applied pressure. As shown in section 4.2, kinematic viscosity and applied pressure have little effect on the vibrational velocity of the orifice plate; therefore, it is considered that this phenomenon is caused by the force from the working fluid acting on the minute particles.

7. Conclusion

Our purpose was to achieve a miniature, lightweight, and low cost hydraulic control valve. Thus, through structural numerical analyses and experiments, we conducted a basic study applying the principle of a particle-excitation flow control valve conceived and developed for pneumatic control.

In the present study, we proceeded to examine a flow control valve with the construction and measurements of past reported pneumatic control valves (outer diameter 10 mm, length 9 mm, number of orifices 12, ring-shaped piezoelectric elements), using silicone oil as the working fluid because of the ease for adjusting its viscosity (kinematic viscosity 1 to 30 mm^2/s). Despite the limitations of this study, the following findings were obtained.

First, regarding the vibration characteristics of the orifice plate:

1) The vibrational velocity of the orifice plate decreases with the use of hydraulic fluid. The main factor causing this is not the viscosity of the hydraulic fluid but its mass.

Regarding the behavior of the minute particles in the hydraulic fluid:

2) The applied voltage required to open the orifices rose with rising hydraulic fluid kinematic viscosity. This is not caused by decreased orifice plate vibrational velocity, but because of the fluid resistance experienced by the minute particles from the hydraulic fluid.

Regarding the developed control valve:

3) Using the miniaturized hydraulic control valve prototype, when the supply pressure was 0.5 MPa, the flow rate reached 891 ml/min for silicone oil with a kinematic viscosity of 1 mm^2/s, and 838 ml/min for oil with a kinematic viscosity of 3 mm^2/s.

4) Three stages were seen in changes in flow rate owing to rising applied voltage: 1) a low flow rate stage, 2) a rapid transition stage, and 3) a saturation stage.

In the present study, the control pressure and hydraulic fluid viscosity were still limited, but the respective causes were identified. We consider that we proved the possibility of realizing a highly miniaturized hydraulic control valve by using the principle of a particle-excitation flow control valve.

In the future, we will study the mounting of this control valve on a low-pressure hydraulic actuator, envisioning a McKibben artificial muscle. We will also study the effects of high pressure, high-viscosity, surface tension, and other physical properties of the fluid on this control valve.

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