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A PIEZOELECTRIC MICROPUMP USING FLUID INERTIA IN PIPE AND ITS APPLICATION

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ABSTRACT

For millimeter-sized fluid-driven micromachines performing power-needed tasks, we proposed a novel micropump using fluid inertia in an outlet pipe. The paper describes the pump structure for higher output power and an application of the micropump to a micro fluid power system. First, a simple nonlinear mathematical model with lumped parameters was proposed and the validity was confirmed comparing the simulation and experimental results. Second, based on the simulations varying the sizes of the outlet pipe and the diaphragm, the pump structure for higher output power was obtained and the validity was verified through experiments. Finally, as an application of the micropump, a position control microsystem was fabricated using the micropump, a microvalve using magneto-rheological fluid valve-body, and a bellows microactuator. The characteristics were experimentally clarified and the validity was confirmed.

KEY WORDS

Micromachine, Micropump, Modeling, Actuator, Magneto-rheological fluid (MRF)

INTRODUCTION

For millimeter-sized micromachines performing power-needed tasks such as micro maintenance systems for 10mm diameter pipelines in industrial plants, microfactories, and so on [1][2], we proposed and have been developing micromachines using fluid power with high power density [2]-[6].
To realize micromachines using fluid power, high output power micropumps are indispensable. However previous micropumps for µTAS (Micro Total Analysis Systems) developed to transport small amount of liquids or gases precisely [7] can not produce high power.
We proposed and have been developing high output power piezoelectric micropumps using resonance drive [3] and the one using fluid inertia in pipe [6]. Especially, the latter micropump has been experimentally clarified to produce higher power. However, the optimal structure has not been clarified yet.
To increase the output power in small size, the paper investigates the pump structure. A nonlinear mathematical model with lumped parameters is proposed and the validity is confirmed comparing the experimental and simulation results. Then, based on simulations using the mathematical model, the pump structure for higher output power is obtained. The validity of the pump structure is verified through experiments. Finally, as an application of the micropump, a position control microsystem is fabricated using the micropump, a microvalve using magneto-rheological fluid (MRF) valve-body, and a bellows microactuator and the characteristics are experimentally investigated.

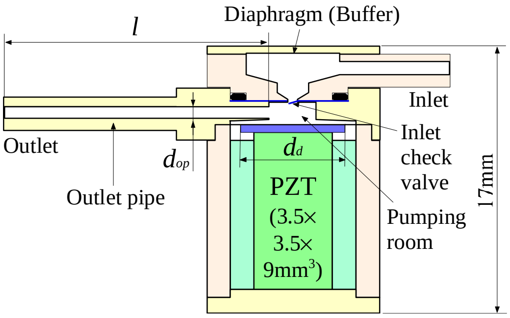
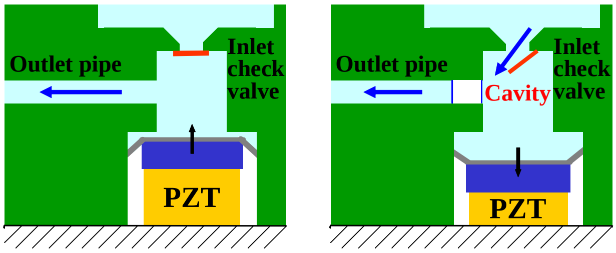


Figure 1 Schematic of micropump using fluid inertia in pipe



(a) Pumping mode (b) Suction mode

Figure 2 Working principle of the proposed micropump

PIEZOELECTRIC MICROPUMP USING FLUID INETIA IN PIPE [6]

Figure 1 shows the schematic of the piezoelectric micropump using fluid inertia in pipe. The micropump consists of a reciprocating pumping room driven by a multilayered PZT actuator, an inlet check valve, and an outlet pipe with small diameter. An accumulator, which is a flexible silicone tube for outflow in this study, is attached to the outlet and the outlet pressure is constant. In the room above the inlet check valve, a plastic diaphragm is installed as a buffer. The working fluid is degassed water.

In a pumping mode shown in Fig. 2(a), the PZT actuator contracts the pumping room, the inner pressure increases, the inlet check valve closes, and the working fluid flows out through the outlet pipe at a high flow velocity. In the subsequent suction mode shown in Fig. 2(b), the PZT actuator expands the pumping room, the inner pressure decreases, and the working fluid flows in through the opened inlet check valve. At the same time, in the outlet pipe, the flow is going to maintain due to fluid inertia in the outlet pipe with a column separation. Thus, the micropump flows out the working fluid in not only pumping but also suction modes and realizes an output flow rate higher than the value estimated with the displacement. Through experiments, we clarified the pumping room pressure modes and realized an output fluid power of 0.21W with 2.3cm^3 in volume.

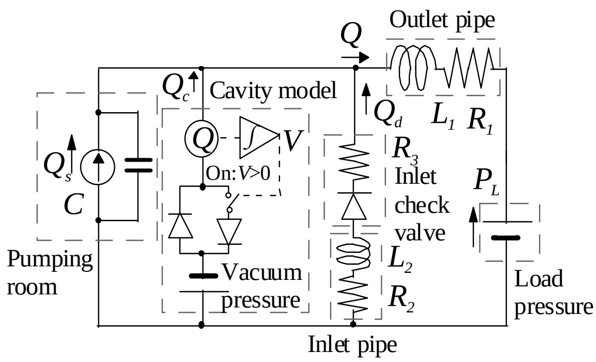
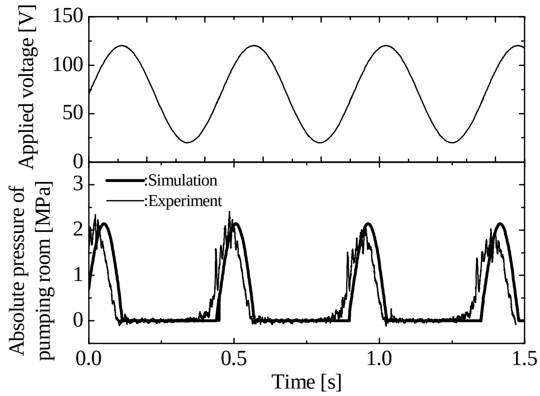
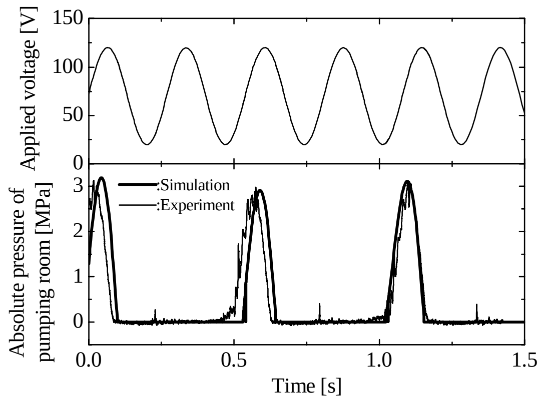


Figure 3 Proposed mathematical model of the micropump



(a) With driving frequency 2.2kHz and load pressure 0.29MPa



(b) With driving frequency 3.7kHz and load pressure 0.32MPa

Figure 4 Experimental and simulation results of pumping room pressure

MATHEMATICAL MODEL OF THE MICROPUMP

Proposition of Nonlinear Mathematical Model with Lumped Parameters

To investigate the pump structure to increase the output power in small size, a simple nonlinear mathematical model with lumped parameters is proposed as shown in

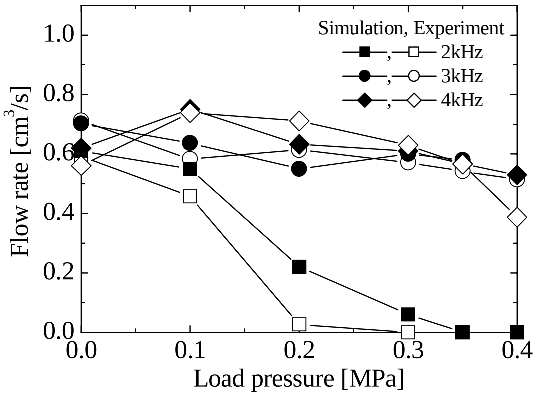


Figure 5 Experimental and simulation results of load characteristics

Fig. 3. Part models are a serial connection of a diode and a resistor R_3 for the inlet check valve, a serial connection of an inductor L and a resistor R for the pipes, a parallel connection of an ac current source and a capacitor C for the reciprocating pumping room. For the column separation, a cavity model is developed. In a suction mode, when the absolute pressure of the pumping room is going to be negative, the cavity model holds the pressure to be 0 supplying fluid from a virtual tank. In the subsequent pumping mode, the cavity model holds the pumping room pressure to be 0 until the inflow in the previous suction mode flows back to the virtual tank. The cavity model is expressed with lumped parameters as shown in Fig. 3.

The resistances are calculated assuming laminar flow, and the inductances are 1.3 times of the calculated value based on basic experiments. The capacitance is obtained considering bulk modulus of the working fluid and elasticity of the PZT actuator.

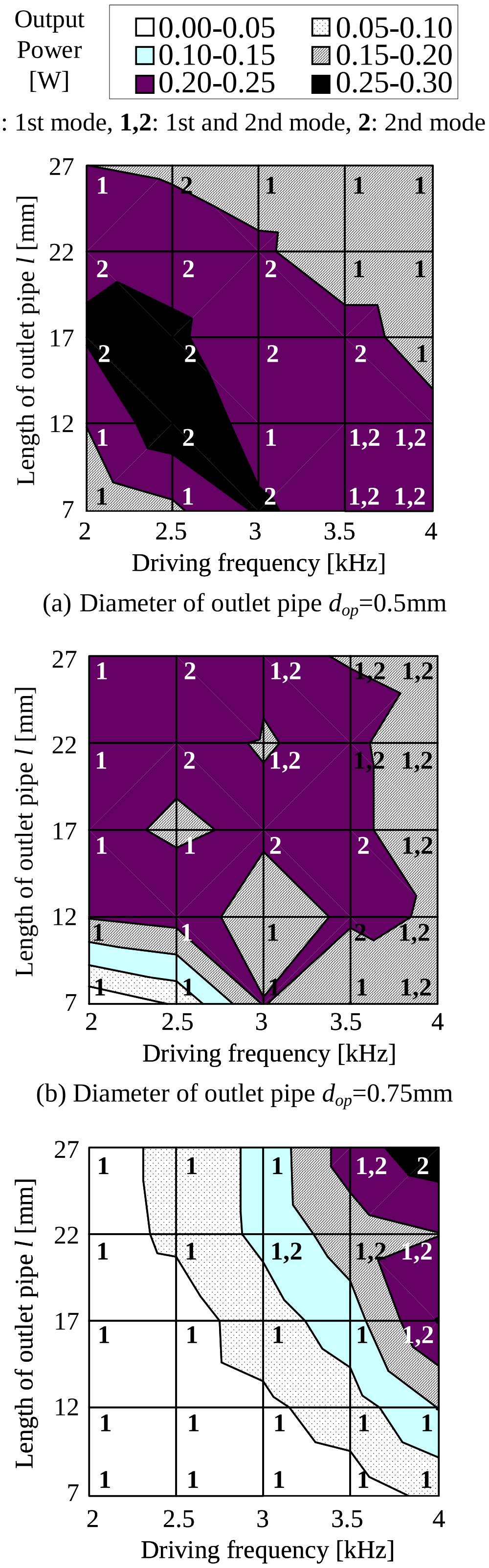
Verification of the Proposed Mathematical Model

Figure 4 exemplifies the simulation and experimental results of the absolute pressure of pumping room. The simulations were performed using MATLAB®. The pulse frequency of the pumping room pressure is the same as the one of the driving frequency in Fig. 4(a), on the other hand, the pulse frequency of the pumping room pressure is twice as large as the one of the driving frequency in Fig, 4(b). The modes are the feature of the micropump and the former is called “1st mode” and the latter “2nd mode”. The peak value and phase of the pumping room pressure coincide with the experimental results for both modes. The average flow rates shown in Fig. 5 also indicate the agreements. The validity of the simple mathematical model was confirmed.

PUMP STRUCTURE FOR HIGHER OUTPUT POWER

Investigations Based on Simulations

To investigate the pump structure for higher output power, simulations were performed with different



(a) Diameter of outlet pipe d_{op}=0.5mm

(b) Diameter of outlet pipe d_{op}=0.75mm

(c) Diameter of outlet pipe d_{op}=1mm

Figure 6 Simulated output power with different sizes of outlet pipe and driving frequencies

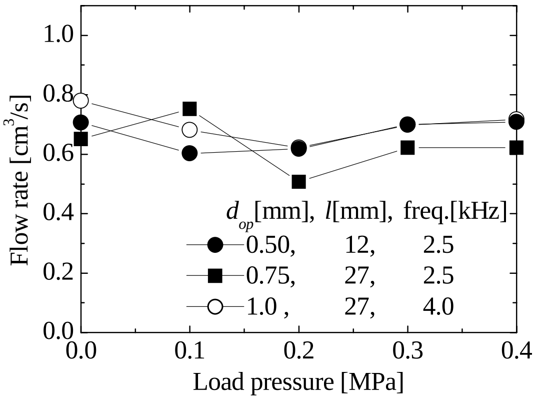


Figure 7 Simulated load characteristics with different sizes of outlet pipe and driving frequencies

Table 1 Simulated output power with different diaphragm diameters

Diaphragm diameter d_d [mm]	3.0			6.3			9.0		
Outlet pipe diameter d_{op} [mm]	0.50	0.75	1.0	0.50	0.75	1.0	0.50	0.75	1.0
Outlet pipe length l [mm]	12	22	27	12	22	27	12	12	22
Driving frequency [kHz]	4.0	4.0	4.0	2.5	2.8	4.0	3.0	2.5	2.5
Output power [W]	0.12	0.14	0.13	0.28	0.29	0.29	0.21	0.25	0.22

diameters d_{op} and lengths l of the outlet pipe shown in Fig. 1 with the established mathematical model. The diaphragm diameter d_d was 6.3mm, diameters d_{op} were 0.50, 0.75, and 1.0mm, and lengths l were 7, 12, 17, 22, and 27mm. The driving frequencies 2~4kHz and the load pressure 0~0.40MPa are in allowable range for the inlet check valve.

Figure 6 shows the maximum output power at each diameter d_{op} and length l of the outlet pipe and driving frequency. Based on the results, it is found that with large inductance with small diameter d_{op} and large length l, the output power is maximized at low driving frequency, and that the 2nd mode produces higher power.

Figure 7 shows the selected results of the load characteristics. As a result, with diameter d_{op}=0.5mm and length l=12mm of the outlet pipe, driving frequency 2.5kHz, and load pressure 0.40MPa, output flow rate of 0.71cm^3/s is obtained, which is 35% higher than the previous experimental value.

Next, the effect with different diaphragm diameter d_d was simulated using the same PZT actuator. The maximum output powers obtained varying diameter d_{op} and length l of the outlet pipe and driving frequency are shown in Table 1. It is found that the diaphragm diameter d_d=6.3mm generates the maximum output power.

Experimental Verifications

Based on the simulation results, micropumps were fabricated as shown in Fig. 8 with diaphragm diameter d_d=6.3mm, diameters d_{op}=0.50, 0.75, and 1.0mm and

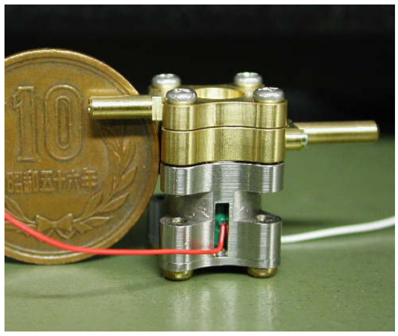


Figure 8 Photocopy of the fabricated micropump

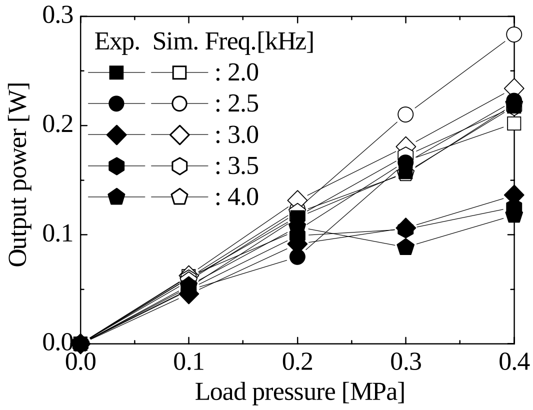


Figure 9 Comparisons of experimental and simulation results

length l=12, 17, and 22mm of the outlet pipe. The PZT actuator (PSt150/3.5×3.5/7, Pizeomechanik Co.) produces the maximum displacement of 4.6μm (applied voltage 100V) and offset 60V and amplitude 100$V_{p\text{-}p}$ were applied. As the load, a variable restriction was installed and the outlet pressure was measured by a semiconductor type pressure transducer (pressure range: 1MPa). The flow rate was measured based on the time to flow out 10g mass.

Figure 9 exemplifies the results. It is ascertained that the maximum output power is obtained with diameter d_{op}=0.5mm and length l=12mm of the outlet pipe, driving frequency 2.5kHz, and load pressure 0.40MPa, which coincide with the simulated results. However, due to variation of capacitance C in reassemble, the maximum output power is 0.22W, which is only 5% higher than the previous value.

APPLICATION TO POSITION CONTROL MICROSYSTEM

Fabricated Microvalve Using MRF Valve-Body [5]

To control fluid power irrespective of machining errors, we proposed a microvalve using MRF valve-body as shown in Fig. 10. MRF has micrometer-sized magnetic particles dispersed in an oily fluid and is pulled by magnetic field. An MRF column is supported in the

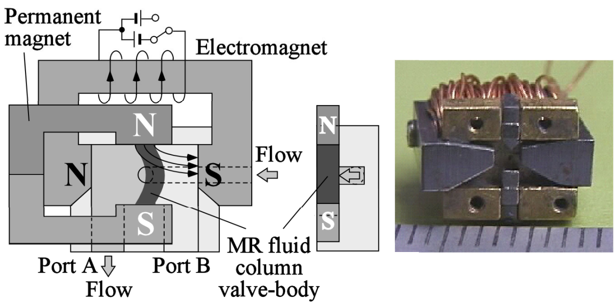


Figure 10 Fabricated microvalve using MRF valve-body

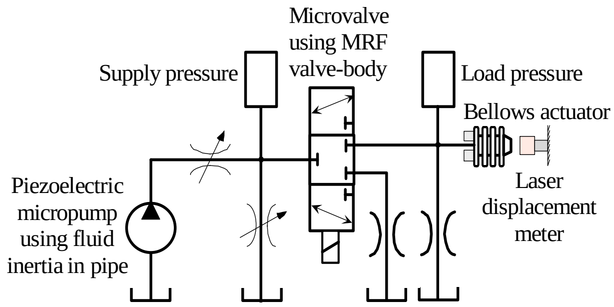


Figure 11 Hydraulic circuit of fabricated position control microsystem

flow channel by a permanent magnet and shuts off the working fluid flow as a valve-body. The MRF column is deformed by perpendicularly applied magnetic field using an electromagnet. With increasing the deformation, the working fluid flow increases. Thus, the valve opening is controlled by the current applied to the electromagnet. The microvalve features simple structure, shut off capability due to the adaptable liquid valve-body irrespective of the larger machining errors, energy saving due to the shut off capability, wide selection of the working fluid that should only be independent from magnetic field and the MRF, and so on. The fabricated microvalve has 10mm×10mm×7mm in size and can control water flow rate from 0 to 30mm^3/s at supply pressure 35kPa.

Fabricated Position Control Microsystem

Utilizing the piezoelectric micropump using fluid inertia in pipe, the microvalve using MRF valve-body, and a bellows microactuator, a position control microsystem was fabricated as shown in Fig. 11. The restrictions at downstream ports of the microvalve have differential pressure 35kPa for flow rate 30mm^3/s. The bellows microactuator has 3.2mm in outer diameter, 3.1mm in length, and 0.40kN/m in spring constant. With large circulation flow, the variation of supply pressure to the microvalve was small. The working fluid was degassed water. Current was applied to the microvalve with a voice coil motor driver (maximum current: ±3A) with dither. Supply pressure and load pressure were measured with semiconductor type pressure transducers (pressure range: 0.1MPa). Output displacement was measured with a laser

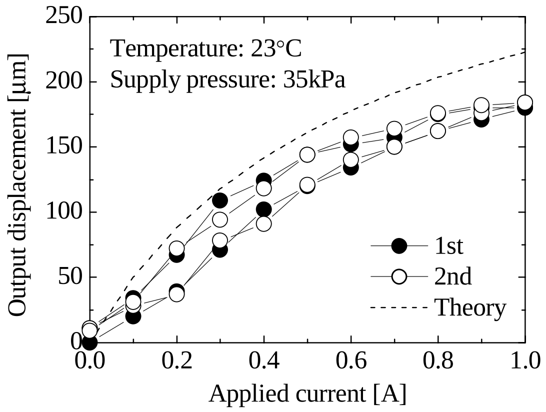


Figure 12 Measured static characteristics of the position control microsystem with open loop control

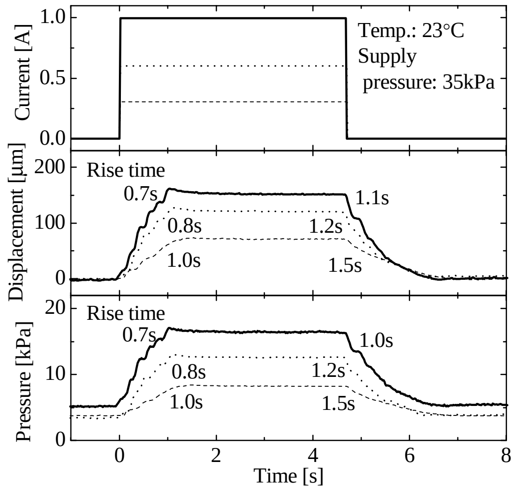


Figure 13 Measured step responses of the position control microsystem with open loop control.

displacement meter (resolution: 0.2μm). The measured values were fetched by a personal computer through A/D converter with sampling frequency 200Hz.

The basic characteristics with open loop control were measured. Figure 12 shows the measured static characteristics. The origin of displacement is the position without current. It is found that the displacement can be controlled up to 180μm with high reproducibility, though there are some hystereses due to friction between the MRF valve-body and valve seat, and that the displacement begins to saturate at current 0.6A. The dotted line in Fig. 12 is theoretically calculated results based on the measured resistance of the microvalve without load. Good agreement is confirmed with some errors due to variation of the MRF valve-body width.

Figure 13 shows the measured step responses. It is found that higher response is obtained with larger current amplitudes for both step up and down. The reason is thought that with high current amplitude, the MRF valve-body approaches to the electromagnetic pole and driving force increases. Also it is found that the

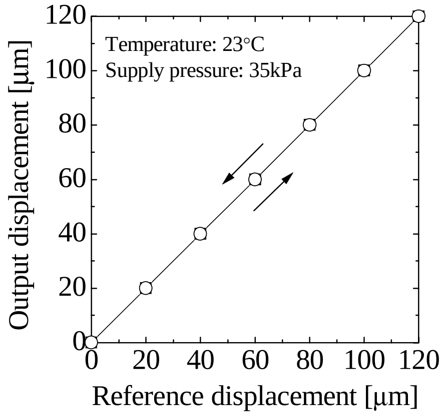


Figure 14 Measured static characteristics of the position control microsystem with PI control

step up response is higher than that of step down. The reason is thought that the force to bend the MRF valve-body by the electromagnet is higher than that by the permanent magnet to recover the shape. There are some stepwise waveforms, which are due to friction between the MRF valve-body and valve seat.

Characteristics of the Position Control Microsystem

A PI control system was constructed by software written in language C. The Proportional gain 0.07A/μm and integral gain 0.03A/(μm·s) were determined based on measured step responses for 10μm amplitude. To prevent the MRF valve-body separation, the applied current amplitude was restricted up to 0.6A.

Figure 14 shows the measured static characteristics. High reproducibility was confirmed up to 120μm.

Figure 15 shows the measured step responses with 0.1Hz square wave. Comparing to open loop system in Fig. 13, rise times decrease and the rise time for step up becomes equal to the value for step down. The reason the rise time for step down is the same as the open loop system is thought that current saturation continues long time. Also, for high step amplitude, the settling time becomes large because current saturation continues long time and wind up occurs highly. The dead time is thought to be due to friction between the MRF valve-body and the valve seat.

CONCLUSIONS

To realize a high output power piezoelectric micropump using fluid inertia in pipe, the pump structure and the application were investigated. The main results are as follows:

(1) A simple nonlinear mathematical model with lumped parameters was proposed and confirmed comparing the simulation and experimental results.

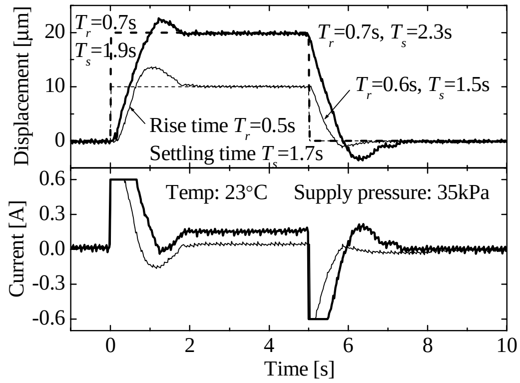


Figure 15 Measured step responses of the position control microsystem with PI control

(2) The pump structure for higher output power was obtained based on simulations using the mathematical model.

(3) The validity of the obtained pump structure was confirmed based on experiments.

(4) The microvalve was applied to a position control microsystem. The characteristics were experimentally clarified and the validity was confirmed.

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