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DEVELOPMENT OF MICROVALVE MECHANISM USING FLUIDICS

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ABSTRACT

In the field of MEMS technology, the high accumulation and high density for making semiconductor devices are rapidly advanced. On the other hand, neither high accumulation nor densification on micro mechatronics are so advanced comparing with semiconductor devices. In our laboratory, it pays attention to microfluidic systems which can control fluids without mechanical moving parts. In this paper, design and fabrication of microfluidic devices with small, light and integration are discussed. A prototype models based on fluidics is fabricated and experimentally investigated. A view point of future application for the micro fluidic devices is also reported.

KEY WORDS

Down Scaling, Fluidics, Laminar Proportional Amplifier, Microvalve, Vent Port

INTRODUCTION

A micromachine and a micro mechatoro device is a general term for devices and integrated systems including parts of 1mm or less. It has a high potential key technology to realize a miniaturization, low power consumption, high density and high integration in many fields such as medical, information and communication, biotechnology and aerospace industry. Recently, according to advance of semiconductor technology, story of the micromachine is not a dream because of development of micro processing and fabrication technologies. Research and development for the micromachine has been widely and actively carried out all over the world for the important technology in the next generation. As a result, a variety of new processing methods and devices for micromachines have been proposed and developed, and begun to walk steadily on the road of practical use.

Especially, according to advance in the biotechnology field the micro fluid control devices such as Micro/Miniaturized Total Analysis Systems (μ-TAS) [1][2], DNA chips and microchips based on capillary electrophoresis become one of the main device in the micromachine. In the medical industry field, the micromachine has been just beginning to be applied a drug delivery system. The drug delivery system (DDS) is a method of surely making the medicine arrive to the treatment part in the inside of a human body without a surgical operation with a present surgical knife [3]. It is possible to make the load reduced to the patient dramatically. Therefore, it is necessary to develop the micro mechatro devices that combines the micro fluid control devices such as micro actuators, micro sensors, micro valves and micro pumps.

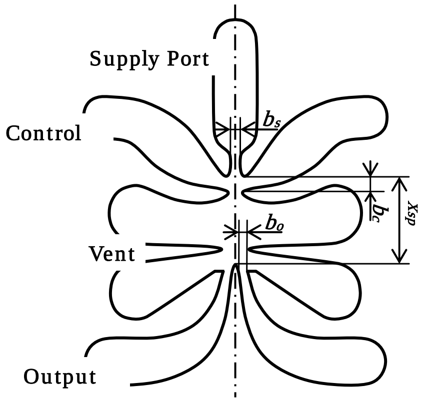
Under an environment marked by the micro size, adsorption, friction, viscocity and abrasion occuring in the surface phenomenon have a large influence on the performance, energy efficiency, durability and reliability of the micromachines. In the micromachine or the micro mechatro device, the micro valve is the most important functional device for the part of the DDS or the unit of the µ-TAS.

It is not suitable for the structure of the valve with mechanical moving parts because of large power consumption. Morerover, it is difficult for the micromachine to assemble many parts in three dimensional structures. Therefore, it is preferable to produce it with complete parts where the mechanism is simple and the parts size is small as much as possible. In our laboratory, it pays attention to microfluidic systems controled fluid flow without mechanical moving parts. In this paper, design and fabrication of microfluidic devices with small, light and integration are discussed. A prototype models based on fluidics is fabricated and experimentally investigated. A view point of future application for the micro fluidic devices is also reported.

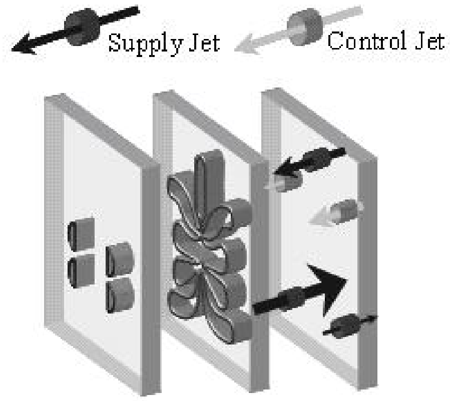
LAMINAR PROPORTIONAL AMPLIFIER

The fluidics is a unique device without mechanical moving parts to control and switch the flow rate and the pressure. The fluidics is the technology of using the internal flow characteristics between walls, i.e., collision of jet flow, generation and settling of turbulence flow, preservation of momentum flow, attachment and separation of jet flow, and resistance or change in relation between the flow rate and the differential pressure. The flow characteristic of the fluidics depends on the shape of the geometry of the flow channel [4][5]. The fluidics has the advantage of easy miniaturization, high reliability and environmental compatibility. Additionally, the method of putting the film and the valve moved by the flow is effectively used according to the condition.

In this research, a laminar proportional amplifier (LPA) in the fluidics is used for control valves. The LPA is the typical analogue element in the fluidics. Figure1 shows the flow channel geometry and the three dimensional structure of the LPA [6]. The LPA consists of supply ports, control ports, output ports and vent ports symmetrically. The important dimension depends on a main nozzle width b_s, a control nozzle width b_c, an output nozzle width b_o and a splitter distance X_{sp}. The dimension of the each part is based on the main nozzle width, and the aspect ratio is selected by one or less to operate because flow range is within a laminar flow of air. Both sides of the plate (Plate2) with the flow channel geometry are sealed up in two plates (Plate1 and Plate3). A main jet emerging from the supply port interacts with flows from the control ports. As a result, a right and left output port receives an inclining main jet flow, and the output differential pressure is proportional to the control difference pressure. The vent port has the role of preventing the influence of flow from output sides to input sides.



(a) Flow Channel Geometry



(b) Structure

Figure 1 Laminar Proportional Amplifier

The LPA has the principle of similitude on the dimension of the flow channel geometry. The multistage LPA is also easily realized to amplify the output signal. It suggests that the operating performance of the LPA may be improved by means of being miniaturized, aligned, arrayed and multistage.

EXPERIMENTS

In this study the standard models of the LPA are designed by the previous model based on [7] and fabricated through a stereolithography method. The stereolithgraphy can fabricate a complex solid model including internal shape in the process of one time and easily reproduce a new shape of form with changing 3D CAD data [8][9]. When we produce the micromachines, it is necessary to reduce the number of parts and assembly process as much as possible. In this respect, the stereolithography is one of most effective method because of manufacturing micro-parts on the whole form. The fabricated LPA consists of three parts of plates; a vent cover (Plate1), a plate with the flow channel geometry (Plate2) and a plate with supply and control ports (Plate3). The final structure of the developed prototype LPA is shown in Figure 2. In the final designing, the Plate 2 are assembled and united with the Plate 3 to reduced number of parts for the fluidics device.

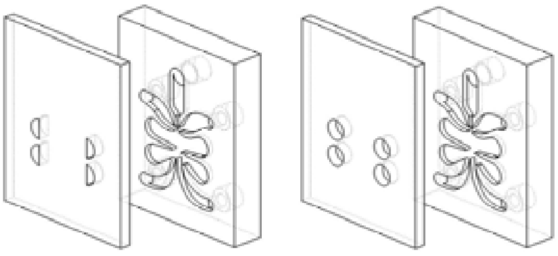
In this paper the standard model of the prototype LPA is called Model_S. The Model_S has the height X_h of flow channel geometry of 12.065mm, the width X_w of 8.89mm, the supply nozzle width of 0.38mm and the thickness of 0.5mm. In the principle of the LPA the shape of the vent ports is one of the important design factor to perform better. The influence for the cover plate and the shape of the vent port for the LPA has not been reported before. We also investigate to effect on the shape of the vent ports on the cover plate fabricated two kinds of vent covers; the semicircular type and circular type of the vent ports.

The Reynolds number *Re* is defined by the following expression as the thickness of the representative length,

$$\mathrm{Re} = \frac{\sqrt{\rho}}{\mu} h \sqrt{2P_S} \qquad (1)$$

where h is the thickness of the element, P_s is the supply pressure at the supply port, ρ is the density of the fluid and the μ is the viscous coefficient of the fluid. When the supply pressure is kept at a constant value, the Reynolds number is dependent on the thickness of the elements, and it isn't involved the width of the supply nozzle b_s. In case of using fluids as air, ρ is 1.024kg/m^3 and μ is 1.808×10^{-5} Pa s. If the supply pressure P_s is kept at 1kPa, the Reynolds number is calculated as 1357 and the air flow at the point of the supply nozzle becomes laminar flow.

Figure 3 shows a system configuration for experimental apparatus. The supply pressure P_s, the control pressures P_{c1} and P_{c2}, the output pressures P_{o1} and P_{o2} are measured with pressure gauges and stored in a microcomputer through an A/D converter, respectively. Amount of minute pressure at the supply and control ports are kept at the constant value by the upstream side of the speed controllers. The static characteristics between pressure difference ΔP_c ($=P_{c1}$-P_{c2}) and ΔP_o ($=P_{o1}$-P_{o2}) are calculated and analyzed.



(a) Semicircular Type (b) Circular Type

Figure 2 Structure of Prototype LPA

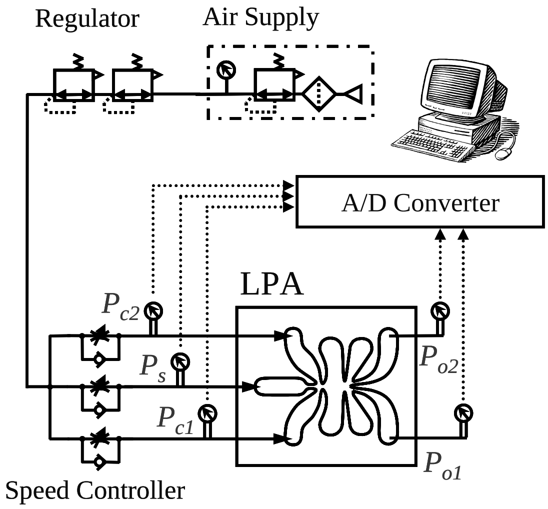


Figure 3 System Configuration of Experimental Apparatus

STATIC CHARACTERISTICS OF LPA

Standard Type of the LPA

On the first stage of our experiments, the static characteristics for the standard models with circular and semicircular types of the vent ports are clarified under the supply pressure P_s of 1kPa. Figure 4 shows the static characteristics between the differential control pressure ΔP_c and the differential output pressure ΔP_o. The ΔP_o is nearly proportional to the ΔP_c in the range of near the origin. The linear characteristics of the pressure gradient are linearized and defined as the pressure gain $G_{p.}$ However, ΔP_o is saturated as increasing ΔP_c, so the range width between the two saturation points on ΔP_c is defined as a linear range L_p. Moreover, the ratio of P_{o1} to P_s under ΔP_c having zero is defined as the pressure recovery ratio R_p. The width of the linear range L_p is dependent on the shape of the vent cover. Table 1 indicates that G_p for the semicircular type is six times comparing to the amount of circular type. The pressure recovery ratio R_p for the semicircular type is 3% larger than the amount of circular type. These results suggest that the output pressure strongly depends on the shape of the vent ports for the LPA.

Next, all pressure data are normalized by the supply pressure in order to verify the static characteristic of the LPA with change of the supply pressure. Figure 5 shows the normalized static characteristics between $\Delta P_c/P_s$ and $\Delta P_o/P_s$ under the standard model with the semicircular type of vent ports. The linear range L_p becomes larger as decreasing the supply pressure. The pressure gain G_p and the pressure recovery ratio R_p become large with increasing the supply pressure as shown in Table 2. Especially, the pressure gain under P_s of 1kPa becomes two times comparing to the pressure gain under Ps of 500Pa.

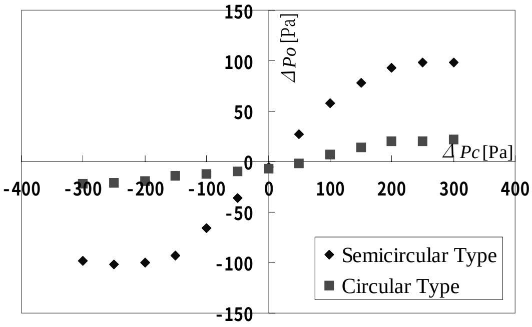


Figure 4 Static Characteristic of Standard Models under Supply Pressure of 1kPa

Table 1 Pressure Gain and Pressure Recovery Ratio with Change of Vent Port

	Semicircular Type	Circular Type
G_p[-]	0.6	0.1
R_p[%]	9.2	6.1

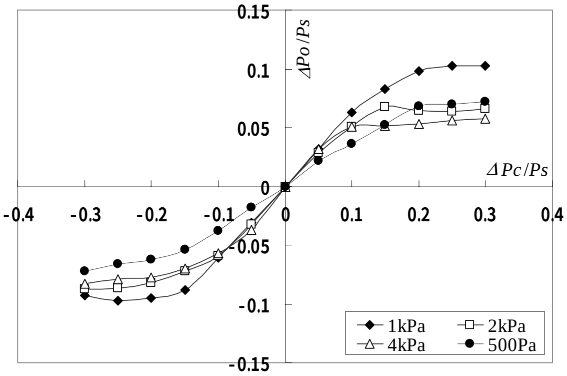


Figure 5 Static Characteristics under Change of Supply Pressure

Table 2 Pressure Gains and Pressure Recovery Ratio under Change of Supply Pressure

P_s	500[Pa]	1[kPa]	2[kPa]	4[kPa]
Gp[-]	0.3	0.6	0.6	0.6
Rp[%]	8.9	9.2	9.8	9.9

Table 3 Dimensions of Prototype LPA

	Model_S (standard model)	Model_8	Model_5
b_s[mm]	0.38	0.304	0.19
b_c[mm]	0.38	0.304	0.19
b_o[mm]	0.513	0.410	0.257
X_{sp}[mm]	3.0	2.4	1.5
h[mm]	0.5	0.4	0.25
X_h[mm]	12.065	9.652	6.033
X_w[mm]	8.89	7.11	4.45

Down scaling of the LPA

In this research, the fluidics is applied to the micro valve. However, there are few reports on the characteristic of the miniaturized LPA since it is difficult to fabricate one. In this section, the influence on scaling of the LPA is experimentally investigated and evaluated the effectiveness of the fluidics. The dimensions of the prototype LPA are tabulated in Table 3. Two different type of the LPA (Model_8 and Model_5) for scaling of the geometry are used to investigate the effect of downscaling comparing to the standard model (Model_S). The downscaling model Model_8 is 0.8 times the Model_5 is 0.5 times as large as the size of the standard model Model_S.

On the second stage of our experiments, the supply pressure is kept at the constant value of 1 kPa and the semicircle type of the vent port is chosen to investigate the static characteristics of the LPA. As shown in Figure 6, the Model_S and the Model_8 are operated normally, but the Model_5 has unstable to operate. It seems the oscillation phenomenon appears since it is too much the supply pressure to generate the flow from the vent to the output side. So we test on the situations of decreasing the supply pressure and changing the vent cover.

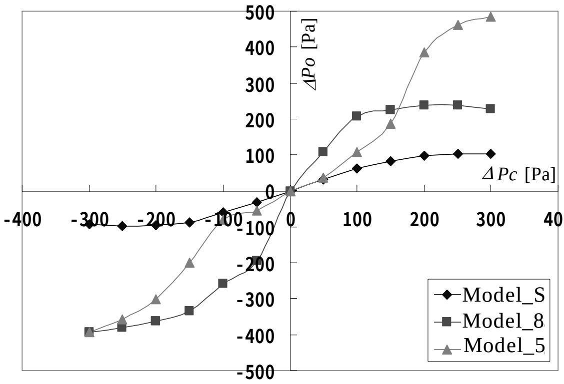


Figure 6 Static Characteristics with Semicircular Type of Semicircle under Supply Pressure of 1kPa

Table 4 Pressure Gain and Pressure Recovery Ratio With Semicircular Type of Vent Port (Supply pressure:1kPa)

	Model_S	Model_8	Model_5
G_p[-]	0.6	2.4	-
R_p[%]	9.2	17.4	-

Figure 7 shows the experimental result under the supply pressure of 500Pa. The oscillatory phenomenon of the pressure in the Model_5 disappeared for decreasing the supply pressure, and L_p becomes larger by miniaturization of devices. The pressure gain and the pressure recovery ratio in using the LPA with circular type of the vent port under the supply pressure of 500P and 1kPa are tabulated in Table 4 and Table 5, respectively. G_p and R_p become larger by downsizing of the fluidics and increasing of the supply pressure. Especially, the pressure gain G_p strongly comes under the influence of the value of the supply pressure.

Figure 8 shows the static characteristics for the LPA with circular type of the vent ports under the supply pressure of 1kPa. The oscillatory phenomenon of the pressure doesn't appear as well as the case of decreasing pressure. The pressure gain and the pressure recovery ratio are tabulated in Table 6. The Model_5 has the pressure gain G_p of 3.3 and the pressure recovery ratio R_p of 0.27. These results indicate the highest value in our experiments. Down scaling of the LPA becomes high performance to operate with under high pressure conditions.

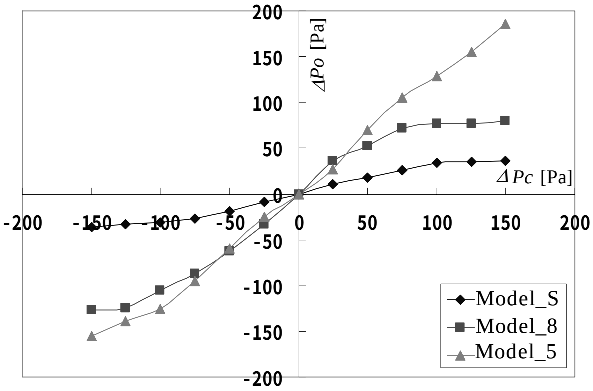


Figure 7 Static Characteristics with Semicircular Type of Semicircle under Supply Pressure of 500Pa

Table 5 Pressure Gain and Pressure Recovery Ratio With Semicircular Type of Vent Port (Supply pressure:500Pa)

	Model_S	Model_8	Model_5
G_p[-]	0.3	1.0	1.2
R_p[%]	8.9%	14.1%	17.7%

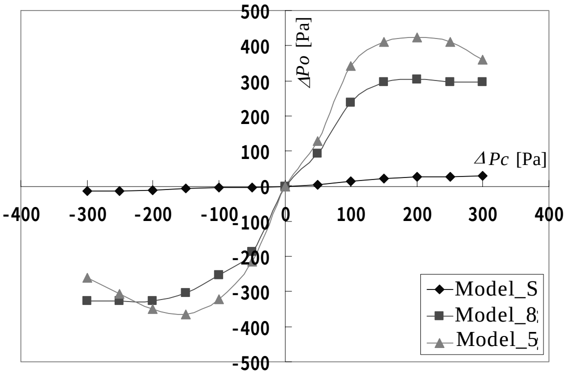


Figure 8 Static Characteristics with Circular Type of Vent Port under Supply Pressure of 1kPa

Table 6 Pressure Gain and Pressure Recovery Ratio With Circular Type of Vent Port (Supply pressure:1kPa)

	Model_S	Model_8	Model_5
G_p[-]	0.1	2.5	3.3
R_p[%]	6.1[%]	18.1[%]	27[%]

CONCLUSIONS

In our research project it has aimed at the development of the micro valve. In this paper the effectiveness of the micro valve using the fluidics has been experimentally investigated. The fluidics is a suitable structure for fabrication under the microscopic environment because of easy uniting and accumulating for multistage devices. The LPA has the principle of similitude on the dimension of the flow channel geometry. It has been confirmed that the normal operation of the LPA has been improved by miniaturization. Moreover the linear range of operation for the LPA between the control pressure and the output pressure has been extended and the pressure recovery ratio and the pressure gain have become larger when the size of the LPA is down scaling. The shape of the vent port greatly affects the range of operation. Therefore the fluidic devices are suitable for using as the micro valve in micro fluid power systems.

The traditional type of the LPA has been fabricated by machining of metals. In our study the LPA is fabricated by the stereolithography for all-in-one design. By use of the stereolithography the edge surface of the flow channel is rough comparing to the traditional machining of metals such as electric discharge machines. In the future work, we develop the micro power fluidics valve that has a smaller size and control ability of high-power with the fine fabrication of minute channel through the microfabrication technology. The integrated multistage LPA is suitable to realize control valves for micro mechatronics under the microscopic world.

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