A PIEZOELECTRICALLY-DRIVEN HIGH FLOW RATE AXIAL POLYMER MICROVALVE WITH SOLID HYDRAULIC AMPLIFICATION

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ABSTRACT

We report a piezoelectrically-driven and hydraulically-amplified axial polymer microvalve. The microvalve is normally open, and is fabricated and assembled primarily with stereolithographically fabricated polymer components. An incompressible elastomer is used as a solid hydraulic medium to convert the small axial displacement of a piezoelectric actuator into a large valve head stroke while maintaining a large blocking force. Also, the axial design of the microvalve enables densely-packed valve arrays. One application of this microvalve is in pneumatic tactile displays, some of which require operation against gas pressures up to approximately 90kPa and switching speeds between 1-200Hz. The current valve design has a maximum static hydraulic amplification ratio of 5 at 30V driving voltage and a maximum valve head stroke of 37μm at 150V. Under a 94.4kPa differential pressure, the flow rate of the valve and the closing voltage measure 785mL/min and 150V, respectively. In addition, the function of the microvalve as an on-off switch for a pneumatic microbubble tactile actuator is demonstrated.

1. INTRODUCTION

Micromachined valves are crucial for a wide variety of microfluidic applications. Fine control of flow rate, relatively fast response compared to conventional valves, low production cost, small size, and low power consumption are examples of favorable microvalve characteristics. Until recently, much research effort has focused on developing microvalves for microfluidic systems that operate under low pressure and require low flow capability at low operating frequency [1-3]. Because of the limitations of micromachining processes and relatively small actuation force and stroke of the valve head, microvalves had limited use in applications that require regulation of flows with high flow rate at high differential pressure, for example a pneumatic tactile display. Previously, we have reported a pneumatic Braille display system using an array of conventional valves and polymer bubble actuators to resolve commonly existing issues, such as insufficient stroke and robustness, in MEMS based tactile display systems [4]. Due to the inherent characteristics of the tactile display system and bubble actuator inflated by a pressurized air source, a densely packed array of valves with switching frequency of up to 200Hz and capable of handling large differential pressure of 90kPa is required.

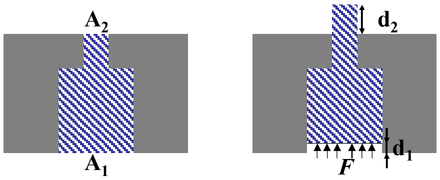
With its high bandwidth, large force, and low power consumption, piezoelectric actuators have become promising candidates for driving microvalves at high pressure and high frequency. However, their drawback is small stroke (up to 0.1% strain) even at a large applied voltage, which restricts orifice gap and in turn limits maximum achievable flow rate. Prior approaches to overcome this drawback include adoption of a stack-type piezoelectric actuator, piezoelectric bimorph structures, and hydraulic amplification mechanisms [5-8]. A leak–proof microvalve provides large sealing force at relatively low voltage by using a stack-type piezoelectric actuator, but the stroke was still insufficient for large flow rate applications [5]. A large valve stroke of 80μm was achieved for a piezoelectric bimorph microvalve, but was limited to very low differential pressure [6]. Roberts *et al.* presented a hydraulically amplified PZT cylinder-driven microvalve with large stroke (20-30μm). However a complex fabrication process including 22 photolithography steps was required [7]. Rogge *et al.* demonstrated a polymer microvalve with PZT bending disk and solid hydraulic amplification, but the PZT disk used had large lateral dimension that prevented the formation of a dense valve array [8].

In this paper, we present the design, fabrication, and experimental results of an axially-amplified piezoelectric microvalve capable of large differential pressure control and capable of being densely packed and integrated with MEMS pneumatic tactile display systems. In our approach, an axially-driven stack-type piezoelectric actuator is vertically integrated with solid means to hydraulically amplify the axial piezoelectric stroke, enabling high flow rate while preserving the potential for spatially-dense valve arrays. The measured flow characteristics suggest its application to liquid and gas microfluidic systems that require the control of high differential pressure flow with high flow rate.

2. DESIGN AND FABRICATION

An important part of the valve design is how to convert the small stroke of a piezoelectric stack actuator into large valve stroke using a hydraulic amplification mechanism while simultaneously maintaining a large force. Macroscale hydraulic amplification systems primarily based on incompressible liquids have existed for a long time, but on the microscale, sealing has been a big fabrication challenge. Solid means can be adopted instead of liquid to reduce the sealing problem. Therefore, this paper focuses on the use of incompressible solid material in the application of hydraulically amplified microvalve.

Figure 1 shows the principle of the solid hydraulic amplification mechanism. When a force is applied axially to the bottom layer of the hydraulic material, causing it to undergo a small deflection, the upper surface of the incompressible material undergoes an amplified deflection. The amplification ratio, defined as the ratio of the displacement of the top and the bottom opening, is, in theory, inversely proportional to the ratio of the areas at top and bottom.

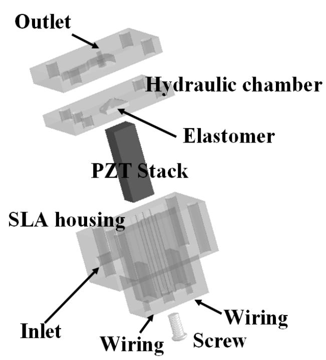


$$\textbf{Amplification ratio} = \frac{d_2}{d_1} = \frac{A_1}{A_2}$$

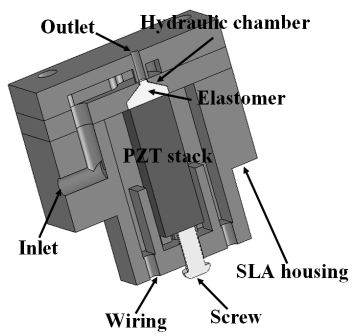
Figure 1: Principle of the solid hydraulic amplification mechanism.

In the design of hydraulic amplification, first it is assumed that the hydraulic amplification chamber compliance is minimal so that the volume change due to chamber deformation is negligible. Secondly, the polydimethylsiloxane (PDMS) elastomer, used as the hydraulic amplification material, is treated as incompressible since the Poisson's ratio of PDMS is 0.5 [9].

Figure 2 shows the exploded and cross-sectional schematics of the designed microvalve with three primary components vertically stacked: a PZT stack actuator as driving element and housing; a hydraulic transmission chamber filled with PDMS elastomer; and a valve chamber connected with outlet, inlet, and valve seat.



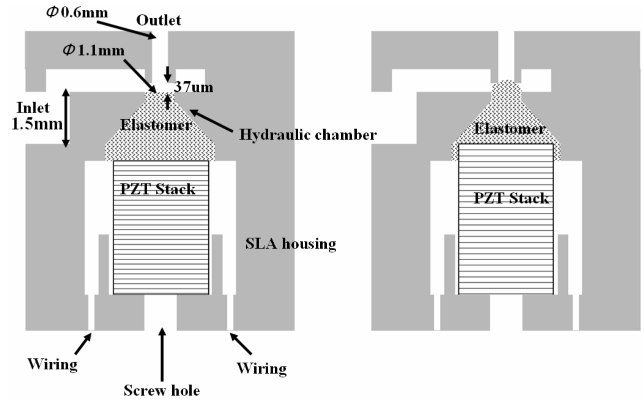
(a) Exploded view



(b) Cross-sectional view

Figure 2: 3-D schematics of the microvalve configuration, showing the geometry of the hydraulic chamber and the inlet and outlet paths.

The operation principle of the microvalve is illustrated in Figure 3. The valve inlet has a diameter of 1.5mm. The valve outlet has a diameter of 0.6mm with a 100μm wide valve seat rim. The valve chamber has a rectangular shape and a 1mm depth. The designed orifice gap is 37μm between the valve head and the valve seat. Taking the friction loss of solid material into account, the hydraulic chamber has been designed to have slanted sidewalls with designed angle and vertical offsets at the top and bottom.



(a) valve open *(b) valve closed*

Figure 3: Operating principle of the normally open piezoelectric polymer microvalve.

The PDMS serves both as a hydraulic amplification medium and as a valve head. When a voltage is applied to the PZT stack, the PZT stack expands axially and pushes the bottom layer of PDMS upwards, generating a small deflection. Because of the hydraulic amplification described in Figure 1, the PDMS valve head deflects upward at an amplified ratio and stops at the valve seat. Another advantage of using PDMS elastomer directly as the valve head lies in its good sealing property, especially for liquid flow. This eliminates the need for complex valve seat structure normally required for leak-proof valve operation.

All three layers were fabricated primarily using stereolithography (SLA) (Viper Si2, 3D Systems). In SLA, the valve parts were fabricated by tracing a laser beam on the surface of a liquid UV-curable epoxy resin layer by layer. The laser source was solid state Nd: YVO_4 and the wavelength used for epoxy resin exposure was 354.7nm. The design of the microvalve and the fabrication sequence is compatible with conventional mass-manufacturing technology such as injection molding and lamination at reduced cost.

The contact surfaces of each layer were finely polished after cleaning and UV post-cure. The hydraulic amplification layer was then bonded to a glass substrate using a wax sheet. PDMS prepolymer (Sylgard 184, Dow corning) was filled into the chamber and cured at room temperature for 24 hours. The hydraulic amplification layer was then released from the glass substrate by dissolving the wax in tricholoroethylene (TCE). The PZT stack (Pst 2×3×7, APC International) with a dimension of 2mm×3 mm×9mm was assembled in the housing layer. A 37μm-thick spacer layer was fabricated by laser cutting a polymer sheet. Finally, the housing layer, the hydraulic amplification layer, the spacer layer and the valve seat layer were assembled with four mechanical screws. The overall dimension of the fabricated microvalve is 6mm×13 mm×9mm as shown in Figure 4.

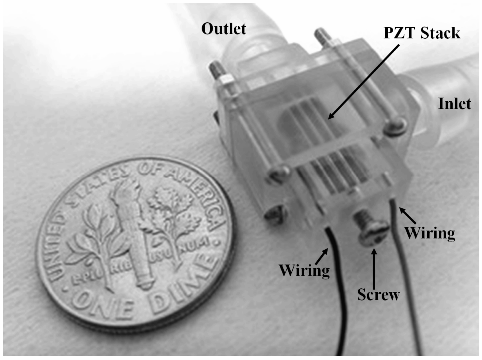


Figure 4: Photograph of a three-layer piezoelectrically driven hydraulically amplified polymer microvalve. Dimensions of the valve are 6mm×13mm×9mm.

3. RESULTS AND DISCUSSION

To verify and characterize the hydraulic amplification between the PZT driving element and the PDMS valve head, the static displacement of the assembled PZT stack actuator and the amplified displacement of the PDMS valve head were measured and plotted in Figure 5.

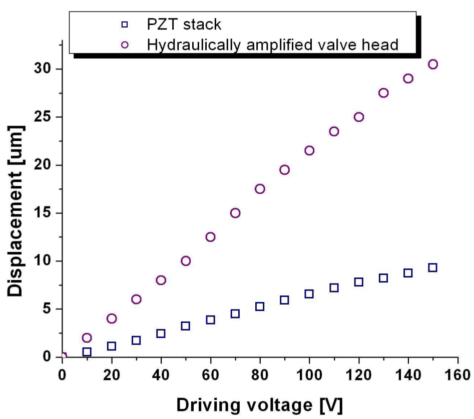


Figure 5: Displacement measurements of PZT driving element and hydraulically amplified valve head.

Based on the data shown in Figure 5, the amplification ratio, defined as the ratio of the displacement of the PDMS valve head to that of PZT stack actuator was calculated and plotted as a function of driving voltage in Figure 6. Three deflection measurements to the nearest 0.1μm were taken and averaged for both the PZT and amplified cases. In this design, the area of the large opening of the hydraulic chamber at the bottom is six times that of the small opening on the top. Although the amplification ratio shows a decreasing trend as voltage increases, the amplification ratio is still larger than 4 over the driving voltage range of 0-150V. A maximum amplification ratio of 5.04 is achieved at 30V. The discrepancy between this measured value and the theoretical value of 6, which is based on the device geometry, could result from several factors, including compliance in the hydraulic chamber, interaction between the hydraulic material and the walls of the hydraulic chamber, and sealing of the PZT actuator to the hydraulic chamber. In this latter case, the assembly tolerance of 100μm between the PZT actuator and the hydraulic chamber may allow some of the PDMS to be squeezed out during operation.

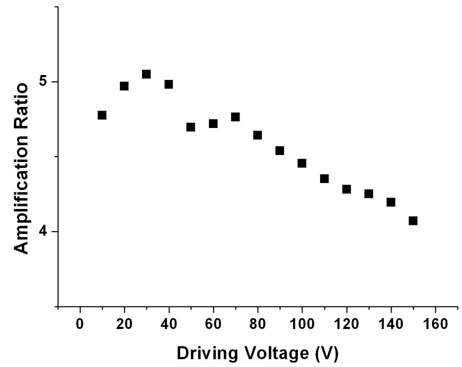


Figure 6: Calculated amplification ratio as a function of driving voltage.

To measure the flow rate, the microvalve was connected to a DC voltage source with 0-150V of actuation voltage and supplied with regulated house N_2 from 0-92.3kPa while the outlet of the valve is maintained at atmospheric pressure. The contact between the PZT stack and the PDMS valve head was realized by adjusting the screw at the bottom of the PZT stack. The gap between the PDMS valve head and the valve seat was initially adjusted to ensure that the valve would be closed at a maximum allowed driving voltage of 150V and inlet pressure of 90kPa.

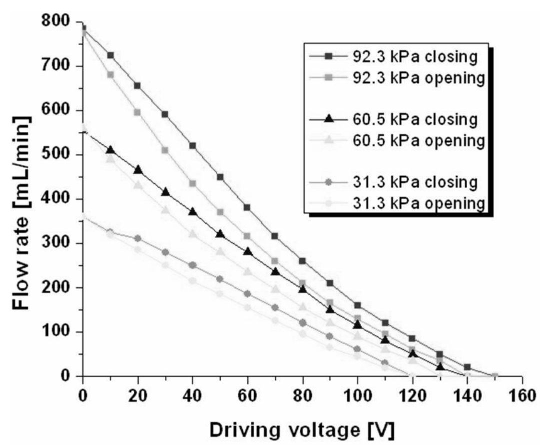


Figure 7: Measured N_2 flow rate as a function of actuation voltage (dc) under various differential pressures.

Figure 7 shows the flow rate-actuation voltage characteristics of the microvalve under three differential pressures. Since the microvalve is normally open, the maximum flow was obtained without any voltage applied. The maximum flow rates for N_2 at 31.3, 60.5 and 92.3kPa are 360, 555 and 785mL/min, respectively. As the driving voltage increases, the flow rate falls due to the reduced height of the flow channel until the valve is completely closed. The closing voltages are 130, 140, and 150V, respectively. Opening voltages are approximately 10V less than the closing voltages in the cases of 92.3kPa and 60.5kPa. At 31.3kPa, the opening voltage is the same as the closing voltage. Figure 8 compares the flow rates of the microvalve as a function of the differential pressure at 4 driving voltages: 0, 30, 60, and 90V, respectively. The curves show some nonlinearity at lower pressure for the cases of 0, 30 and 60V.

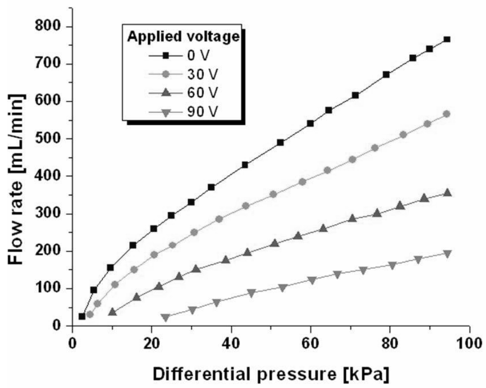
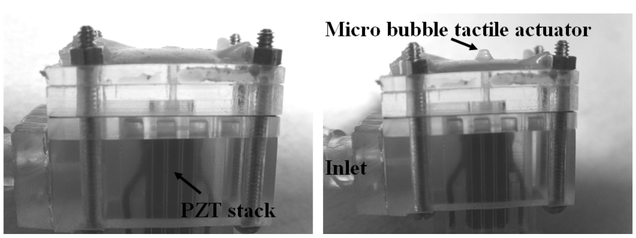


Figure 8: Measured N_2 flow rate as a function of differential pressures at different actuation voltages (dc).

The function of the microvalve as an on-off switch for a pneumatic microbubble tactile actuator has also been demonstrated in Figure 9. The valve was first closed by applying a voltage of 150V. A differential pressure of 90kPa was then applied to the inlet of the valve. As shown in Figure 9(a), the valve successfully kept the microbubble at OFF-state. Next, voltage was turned off and the microvalve was opened. As a result, the microbubble actuator was pressurized (ON-state) and inflated until the pressure reached the level applied to the inlet. Finally, 150V voltage was applied and the valve was closed again. The microbubble actuator remained at ON-state even after the removal of the inlet pressure (Figure 9(b)), which demonstrated the good sealing of the valve.



(a) Bubble actuator OFF *(b) Bubble actuator ON*

Figure 9: Demonstration of successful control of a tactile actuator for a pneumatic tactile display.

4. CONCLUSION AND FUTURE WORK

In this paper, a normally open, high flow rate microvalve utilizing a PZT stack actuator and a solid hydraulic amplification mechanism has been designed, fabricated, and tested. The microvalve was fabricated by SLA technology and static flow characteristics were evaluated with N_2. The microvalve requires reasonable closing voltages at a large supply differential pressure and large flow rate, i.e., 150V for 92.3kPa and 785mL/min. The adjustable initial orifice gap permits flexible fluid regulation over a large range of differential pressure with high flow rate. Also, the proposed axial polymer microvalve shows the feasibility of being densely packed and integrated with the miniaturized pneumatic tactile display systems. In addition, micromolding technology will be investigated and adopted for the low cost mass-manufacturability of the microvalve.

5. ACKNOWLEDGEMENT

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