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Performance of a serial-connection multi-chamber piezoelectric micropump

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Abstract: The concept and structure of serial-connection multi-chamber (SCMC) micropumps with cantilever valves is introduced. The SCMC micropump, which can be manufactured using conventional production techniques and materials, has a multi-layer circular planar structure. The border-upon piezoelectric actuators of a SCMC micropump work in anti-phase, as a result the pumping performance is similar to that of several single-chamber pumps running in series. The theoretical analysis shows that the pumping performance of a SCMC micropump depends not only on the characteristic and geometrical parameters of the piezoelectric actuators, but also on the number of pump chambers. Both flowrate and pressure of a SCMC pump can be enhanced to a certain extent. Four piezoelectric micropumps with different chambers were fabricated and tested. The testing results show that the enhancing extents of the flowrate and pressure of a SCMC piezoelectric micropump are different. The maximum flowrate and pressure of the four-chamber pump achieved are 2.5 times and 3.6 times those of the single-chamber pump achieved.

Key words: micropump; piezoelectric actuator; multi-chamber; cantilever valve

1　Introduction

Micropumps are the essential components in micro-fluidic system which has emerged as a popular area of research with the development of micro-electro-mechanical system (MEMS). Since one of the early piezoelectric micropumps for insulin delivery was fabricated in 1978, more and more efforts have been made in the research of micropumps[1]. Due to their precisely controlled flowrate, micropumps present promising applications in analytical chemistry, medical treatment, pharmacy, bioengineering, fuel-drop generator for automobile heater, etc. Among the large number of actuation methods such as thermopneumatic[2], electrostatic [3-5], piezoelectric[6-16], shape memory alloy (SMA) actuation[17,18], electromagnetic[19], etc, piezoelectric actuation presents its advantages by comparatively high stroke volume, high actuation force and fast mechanical response.

The piezoelectric diaphragm micropumps can be divided into the pumps with check valves and valveless pumps according to the structure of their valves. Compared to the flowrate of valveless piezoelectric micropumps, the flowrate of the piezoelectric micropumps with check valves is higher, more precise and without backflow. At present, most of micropumps are of single-chamber and both the flowrate and pressure are too low to be applied widely. The previ-

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ous investigations of the piezoelectric pumps show that with the increasing of the actuator diameter the flowrate increases, while the pressure decreases[6,12] which suggests that the flowrate and pressure can not be enhanced simultaneously by changing the diameter and thickness of the piezoelectric actuator of a single chamber pump. One of the effective methods to enhance flowrate is to increase the pump chamber. Several double-chamber valveless piezoelectric pumps have been introduced since then[13-14]. Because the two chambers of the above pumps are of parallel-connection, only the output flowrate increases compared with the one-chamber pump. In this work, we present a new type of serial-connection multi-chamber micropump, which can enhance the flowrate and pressure simultaneously. To find out the influence of the number of chambers on the performance of SCMC micropumps, four piezoelectric micropumps with different chamber numbers were fabricated and tested.

2 Piezoelectric diaphragm actuator

Piezoelectric micropumps can transfer mechanical energy into fluid movement while the piezoelectric diaphragm (PZT actuator) is operating in a bending vibration mode. This vibration mode shows its advantage of lower natural frequency over a radial and width mode with the same dimensions. Since the output performance of the micropump is affected directly by the geometrical parameters of PZT actuator, it can be denoted by the displacement and pressure of the center. According the reference[6], when the operating frequency is well below the resonant frequency of the actuator, the central displacement of the actuator can be expressed as

$$\delta=\frac{3}{8}d_{31}\frac{d^2}{t^2}U \ , \tag{1}$$

where δ is central displacement, U is driving voltage, d and t are the diameter and thickness of the piezoelectric diaphragm, and d_{31} is the piezoelectric constant. The PZT actuator is assumed to have a spherical displacement when a voltage is applied, and the volume displaced is given by

$$\Delta V=\frac{3\pi}{64}d_{31}\frac{d^4}{t^2}U \ , \tag{2}$$

When the influence of the metal membrane isn't taken into account, the output flowrate against zero pressure head can be expressed as

$$Q(U,f)=\frac{3\pi}{32}d_{31}\frac{d^4}{t^2}\eta Uf \ , \tag{3}$$

where η is the check efficiency of the check valves. When the movement of the check valves is a driven harmonic oscillation, the actions (opening and closing) of the passive check valves always lag behind the vibration of the actuator. Therefore, both the valve opening (defined as frequency-dependence amplitude) and the phase shift (φ, between the movement of the actuator and the valve) exert great influence on the check efficiency of the cantilever valves. When the driving frequency is much lower than the natural

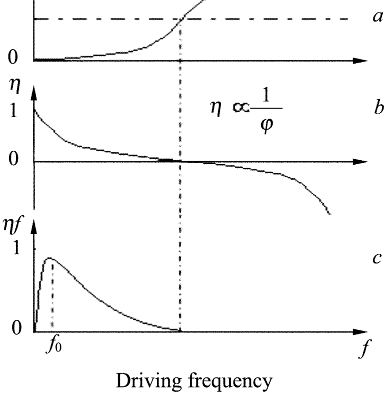


Fig. 1 Relationship between the check efficiency of valve and the frequency

frequencies of both the check valve and the actuator, the valve opening and the actuator deflection can be considered as constant. In this case, the output performance of the pumps mainly depends on the check efficiency of the valve, which decreases with the increasing of the phase shift ($\eta \propto 1/\varphi$). Thus, there will be a lower frequency (f_0) for the product of η and f_0 to reach maximum. Consequently, the output flowrate is nonlinear with the working frequency, and there is an optimal working frequency f_0 (well below the resonant frequency in the air), at which the maximal output flowrate can be achieved. The relationship among them can be illuminated in Fig. 1. The Eq. (3) is valid only for the case when $f \leqslant f_0$.

Simultaneously, according the reference[6], the pressure generated by the PZT actuator can be expressed as

$$P(U)=\frac{12\pi Y_{11}^{D} d_{31}}{4.5\pi Y_{11}^{D} g_{31} d_{31}+1}\frac{t}{d^{2}}U \ , \qquad (4)$$

where Y_{11}^D is the elastic modulus of PZT actuator, and g_{31} is the piezoelectric constant.

The Eq. (3) and Eq. (4) show that many factors have effects on the output value of a piezoelectric micropump, such as working parameters (voltage and frequency) and geometrical parameters of the PZT diaphragm. We can raise the flowrate by decreasing the thickness or increasing the diameter or increase the output pressure by decreasing the diameter or increasing the thickness. For the limited maximum driving voltage, it is difficult to increase the flowrate and pressure simultaneously by changing the geometrical parameters of the PZT diaphragm. Therefore, a new type of multi-chamber micropump is presented to enhance the output performance.

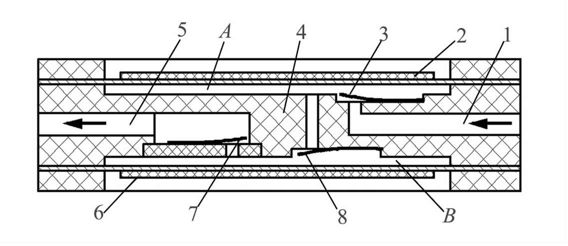
3 Structure and working principle

Most of the micropumps are designed as single chamber once with relatively low output performance. To enhance flowrate as well as pressure, the SCMC micropumps with membrane valves are presented. The inlet and outlet of chambers the SCMC micropump are connected serially. The structures of the double-chamber pump and four-chamber pump are shown in Fig. 2. At the same time, the PZT actuators of the border-upon chamber should work in anti-phase. When an alternating voltage is applied, bending displacement occurs on the PZT diaphragm and the volume of the chamber changes accordingly.

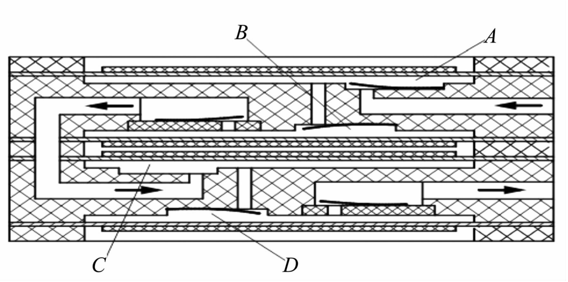
Taking the double-chamber pump for example (Fig. 2(a)), the two diaphragm actuators and the valve body are composed of the sealed chamber (A) and chamber (B). While the PZT actuators operate in the anti-phase mode, the volume of the two chambers changes alternately. i. e. when the actuator (2) is bending upward, underpressure occurs in chamber (A). Meanwhile, the actuator (6) is also bending upward, overpressure is generated in chamber (B). Likewise, when the pressure in chamber (A) is increasing and the pressure in chamber (B) is decreasing. The decrease of the pressure in chamber (A) makes its inlet valve (3) open and the outlet valve (8) close, and transfers the fluid into chamber (A) through the inlet (1). At the same time, the increase of pressure in chamber (B) pushes its inlet valve (7) open, and transports the liquid out of the chamber (B) through outlet (5). On the other hand, when chamber (A) discharges liquid out, chamber (B) sucks the liquid in. The working principle of the diaphragm pump can be described as a periodic process. In this operation mode, the output performance is equivalent to that of two single-chamber micropumps operating in series. Theoretically speaking, the output pressure should be the sum of that of all the chambers. Taking the influence of other elements into consideration, the pressure of a SCMC micropump can be expressed as

$$P=\lambda\Sigma P_i \qquad (i=1,2,\cdots,n)\ , \tag{5}$$

Where λ is the coefficient, and n is the number of chambers.



(a)Double-chamber pump



(b)Four-chamber pump

Fig. 2 Schematic cross-section of the multi-chamber micropumps

The flowrate of the multi-chamber pump is the rate through inlet or outlet, and the pressure difference between the inlet and outlet is P. According to the relationship between the flowrate and pressure, flowrate of the SCMC pump is

$$Q=C_vA\sqrt{\frac{2P}{\rho}}=C_vA\sqrt{\frac{2\lambda\Sigma P_i}{\rho}}\ , \tag{6}$$

Where C_v is the velocity coefficient, A is area of the valve orifice, and ρ is liquid density. Eq. (5) and Eq. (6) suggest that both pressure and flowrate can be improved to a certain extent with increasing the number of serial-connection chambers.

4 Design and fabrication

As mentionedabove, piezoelectric micropumps have applications in analytical chemistry and medical treatment. Therefore, appropriate fabrication methods, materials, and assembly should be selected to meet the requirements of mass production so as to make the price as reasonable as possible. Taking the one-chamber pump for example, the fabrication process is introduced below.

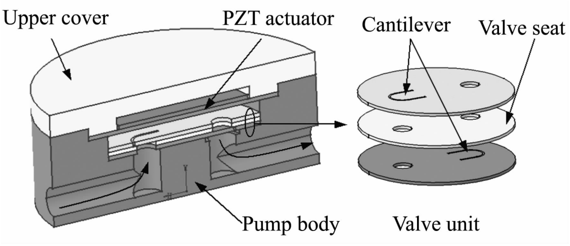
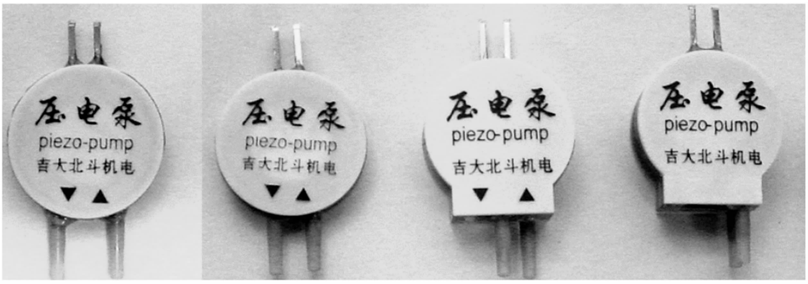


Fig. 3 Assembly structure of one-chamber micropump

The assembly structure of the one-chamber pump is shown in Fig. 3. At present, both the pump body and pump covers are made of PMMA and manufactured by a precision-carving machine. In the case of mass production, they can be fabricated by cast plastic. The two important components of such a piezoelectric pump are the actuator and check valve. To obtain repeatability of the micropump, all of the components should be fabricated and located carefully. The cantilever valves were made of beryllium bronze membrane 0.05 mm in thickness and fabricated also by the precision-carving machine to obtain sufficient accuracy. The valve size of cantilever type was designed to be 4.0 mm×1.3 mm. The valve orifices and the inlet/outlet orifices are 0.5 mm and 0.8 mm in diameter, respectively. The finished valve parts were adhered to the surfaces of the valve seat(Φ9×0.2 mm) beforehand, then clamped with a position-setting jig and heat-preserved in a thermostatic oven. The actuator, which is available commercially, consists of a circular piezoelectric membrane (Φ8×0.1 mm) glued on nickel membrane (Φ12×0.1 mm). After the valve unit and the actuators were assembled, a pump chamber (Φ9×0. 1 mm) was set up. Four piezoelectric pumps with different numbers of the pump chamber were fabricated with the same materials and method to contrast with each other. The finished pumps are shown in Fig. 4.



(a) 1-chamber pump (b) 2-chamber pump (c) 3-chamber pump (d) 4-chamber pump

Fig. 4 Photo of the multi-chamber piezoelectric micropumps

5 Experiment and analysis

The fabricated pumps were tested with water as working medium at the driving voltage of 50 V. The AG1200 Arbitrary Waveform Generator and the 7058 Power Amplifier were used as the source of the pump. The driving force was double-channel voltage signals. In this work, a series of experiments were conducted to find out the performance of the multi-chamber pumps.

Fig. 5 and Fig. 6 show the frequency characteristics of flowrate and pressure of the single-chamber pump and the double-chamber pump at operating voltage of 50 V. The curves indicate the changing regular of flowrate against zero pressure and pressure against zero flowrate with the increasing of driving frequency, respectively. The test results have a good agreement with those of theoretic analysis. Both flowrate and pressure are nonlinear with driving frequency. There are optimal frequencies for them to achieve maximum. The comparison of the optimal frequencies suggests that the flowrate and pressure of a given pump share the same optimal frequency, and that the optimal frequencies of different pumps are almost the same (about 150 Hz). Therefore, a conclusion can be drawn that the optimal frequency of a SCMC piezoelectric pump is decided mainly by the actuator as well as the valves, but not by the number of pump chambers. With the actuators and valves used in this paper, the optimal frequencies of the three-chamber and the four-chamber pumps are also about 150 Hz.

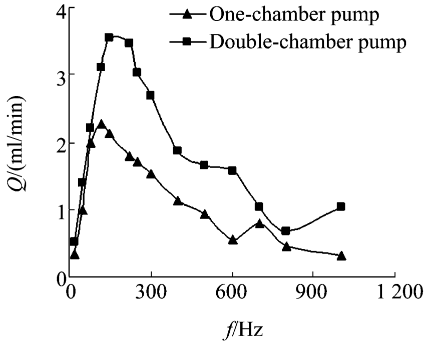


Fig. 5 Relationship between flowrate and driving frequency

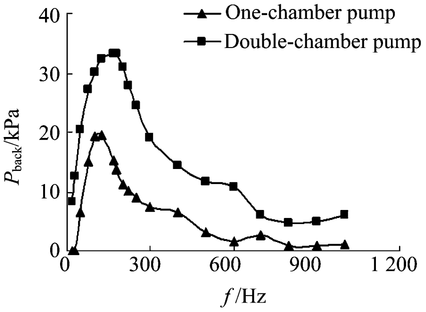


Fig. 6 Relationship between pressure and driving frequency

To compare the enhancing degree of flowrate and pressure with the increasing of pump chambers, all of the fabricated pumps were test at voltage of 50 V and frequency of 150 Hz. The tested results are shown in Fig. 7. The maximum flowrate of the four-chamber pump achieved is 5. 6 ml/min, which is 2. 5 times that of the single-chamber pump achieved (2. 27 ml/min). The maximum pressure of the four-chamber pump achieved is 69 kPa, which is 3. 6 times that of the single-chamber pump achieved (19. 5 kPa). Based on the test results above, the coefficient (λ, in Eq. (5)) can be worked out ($\lambda \approx 0.9$). Two curves show that the enhancing degree of pressure is greater than that of flowrate.

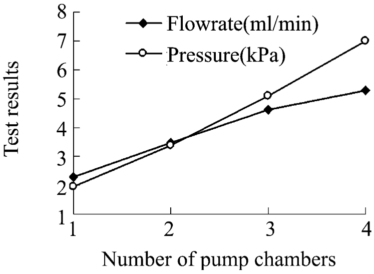


Fig. 7 Relationship between the flowrate/pressure and the number of pump chambers

6 Conclusions

In order to improve the flowrate and pressure of piezoelectric micropump simultaneously, a new type of multi-chamber serial-connection piezoelectric micropumps is presented. The theoretical study shows that the capability and geometrical parameters of the PZT actuator exert great influence on the output performance of a micropump, i. e. decreasing the thickness or increasing the diameter of the actuator is helpful for the improvement of the flowrate. On the other hand, decreasing the diameter or increasing the thickness is advantageous for the augment of the pressure. Moreover, the serial-connection of chambers can significantly enhance flowrate as well as pressure.

Four SCMC piezoelectric micropumps (with one-chamber, double-chamber, three-chamber and four-chamber, respectively) were fabricated with the piezoelectric membrane of 0. 1 mm in thickness and 8 mm in diameter. The pumps were tested with water as the working medium at the applied voltage of 50 V and frequency of 150 Hz. The test results show that both flowrate and pressure of the SCMC micropumps rise to different extents with the increasing of the number of pump chambers. The improvement of output pressure is greater than that of flowrate. This is in accordance with the theoretical analysis. The maximum flowrate and pressure of four-chamber pump achieved are 5. 6 ml/min and 69 kPa, respectively, which are 2. 5 times and 3. 6 times those of the single-chamber pump achieved. On the other hand, because of the valve-check efficiency decreasing with the increasing of the phase shift, pumping flowrate/pressure is nonlinear with driving frequency. There is an optimal frequency, which depends on the piezoelectric actuator as well as the valves, for flowrate/pressure to achieve maximum. The optimal frequencies of the different pumps with the same kind of actuators and vales are almost the same.

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