Vibration performances of polymeric micropump actuated by $PbZrTiO_3$ bimorph

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The check valve micropump can easily reach a high-flow rate, and it has promising application prospects in microfluidic devices and artificial organs. There are several vibrating parts in the check valve pump, including the actuator, membrane and valves. The vibration performances of these parts have a coupling influence on the performance of the micropump. In the work reported in this Letter, four kinds of micropumps with different valves and actuators were designed and fabricated, and the vibration performances of the vibrating parts were analysed by the finite element method. Then, the performances of each kind of micropump were studied by frequency sweeping experiments. The factors affecting micropump performance were determined, and the experimental results approximately coincide with the theoretical analysis. This research provides a theoretical and experimental basis for the design and optimisation of the micropump.

1. Introduction: The micropump, as an actuator for microfluid transmission and control, has been widely used in drug delivery, biological and chemical analysis and microelectronics cooling [1, 2]. The reciprocating micropump is the most extensively studied micropump, and it can basically be divided into two types: the check valve micropump and the valveless micropump. The valveless micropump is hard to enlarge and it is difficult to precisely control the flow rate because of its inherent issues such as back flow and random flow. However, the micropump with valves can reach a high-flow rate and also can realise linear control. In addition, it has mature manufacturing technology [2, 3].

The general actuation mechanisms of reciprocating micropumps include piezoelectric [4, 5], electrostatic [6], electromagnetic [7], thermo-pneumatic [8] and shape memory alloy (SMA) actuation [9] and so on. Compared with other actuations, piezoelectric actuation has many merits such as large actuation force, fast response time, good reliability, a simple structure, is miniature and of light weight. Therefore piezoelectric actuation is the most commonly used drive mode, and the piezoelectric micropump has promising application prospects.

The performance of the micropump actuated by $PbZrTiO_3$ (PZT) is affected by many factors. The previous studied mainly focused on static factors such as voltage, valve thickness, channel shape, membrane thickness and so on. Several researches have studied the influence of the actuator on the performance of the micropump, however most of them were for valveless micropumps [10–12]. Among the few researches of micropumps with valves, the influences of these components were separately analysed [13], or the valves were assumed to be working perfectly so ignored for analysis [14].

In the micropump, there are several vibrating parts including the PZT actuator, membrane and valves. The vibration performances of the vibrating parts have a coupling influence on micropump performance, but few researches of this aspect have been reported. Hence, it is necessary to perform a comprehensive analysis to find out the influencing factors in a better manner.

In the work reported in this Letter, four kinds of micropumps with different valves and PZT actuators were designed and fabricated. Then, the vibration characteristics of the vibrating parts were simulated by the finite element model (FEM). Lastly, the flow performances of these micropumps were studied by frequency sweeping experiments. On comparing the experiments results with finite element analysis, factors influencing micropump performance were determined.

2. Structure: The check valve micropump is widely used in the biochemical field. Considering the biological compatibility, the micropump designed in this Letter is made of polymeric materials. The material of the pump body was polymethylmethacrylate (PMMA) substrate of 2 mm in thickness, and the check valves were made of SU-8 photoresist. The structure of the polymeric micropump is shown in Fig. 1. It is composed of a pipeline, an inlet and an outlet valve deck, a valve, pump body, membrane and PZT bimorph. The micropump can be divided into an inflow module and an outflow module, and the structures of the two modules are oppositely designed, but they all have unidirectional continuity. A closed chamber is formed when a membrane is glued on the groove at the bottom of the pump body. Lastly, the PZT bimorph is fixed on the chamber forming a cantilever structure. The centre of the bimorph is connected to the membrane to drive its vibration.

Two kinds of pump bodies in different sizes were designed. The size of the large one is 30×20 mm, and that of the small one is 20×16 mm. Two kinds of PZT bimorphs in different sizes were applied to drive the micropumps, and the size of the PZT bimorph is the same as that of the pump body which it drives. Also, two kinds of valves were designed as shown in Fig. 2. The structures of the valves were three-beam cantilever and five-beam cantilever, respectively.

3. Finite element analysis of the micropump: Assume that the valves work perfectly: which means when a forward pressure is imposed on the valve, the valve opens the channel completely; and when a reverse pressure is imposed on the valve, the valve shuts off the channel completely. When the backpressure is zero, the flow rate of the pump can be calculated by the following equation:

$$R(f,\ U) = f\ \Delta V(f,\ U) = f\ 2/3\ D_{mid}\ A \qquad (1)$$

where f is the actuation frequency, U is the actuation voltage applied on the bimorph, R (f, U) is the flow rate of the pump, D_{mid} is the centre displacement of the membrane and A is the size of the membrane.

Equation (1) shows that the flow rate is proportional to the actuation frequency and the centre displacement of the membrane for a fixed micropump. The centre displacement of the membrane

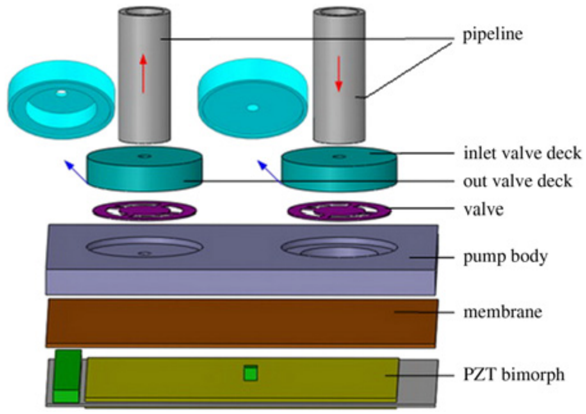

Figure 1 *Explosive view of the micropump*

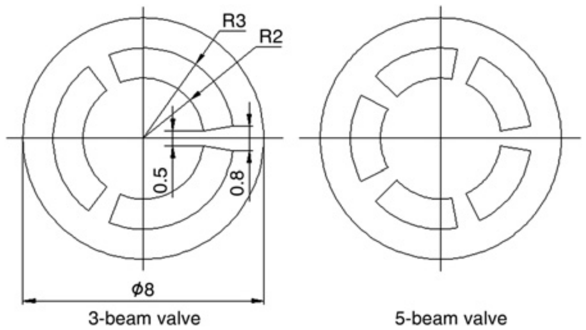

Figure 2 *Structures of the valves*

is determined by the PZT bimorph. The amplitude of the bimorph changes with increase of the frequency, it reaches the maximum at its harmonic frequency. However, in reality, the valve performance plays a very important part in the micropump. It is affected by the pressure difference of the chamber, and it reaches the best at the harmonic frequency of the valve in water. Therefore the flow rate would have several peaks with the increase of actuation frequencies.

3.1. Harmonic response analysis of the PZT bimorph: Select the full method to analyse the harmonic frequency of the PZT bimorph. The middle layer of the PZT bimorph is copper with a thickness of 0.09 mm, which is built by a Solid 92 unit. On both sides of the copper layer are PZT sheets with thickness of 0.25 mm, which are built by the Solid 45 unit. The copper layer and the PZT layers are combined with the 'Glue' order. PZT (1/10 of the whole length) is applied by simple restraint, and zero voltage is applied on the top and the bottom of the copper layer. 105 V voltage is applied on the small-size PZT, and 135 V voltage is applied on the large-size PZT. The harmonic frequencies of the small-size PZT and the large-size PZT are 1000 and 650 Hz, respectively.

3.2. Modal analysis of the valves in water: A fluid-solid coupling model was used to analyse the harmonic frequency of the valve in infinite static water. The valve is built by the Solid 45 unit, and water is built by the Fluid 30 unit. Fluid units connected with the valve are defined as structure existence, and the other parts are defined as structure deficiency. Apply the asymmetric method to operate model analysis, and the first-order harmonic frequencies of the three-beam valve and five-beam valve are 585 and 928 Hz, respectively.

3.3. Modal analysis of the pump body with water: Water is built by Fluid 30, and the pump body is built by the Solid 92. Define the contact surface between water and PMMA as the fluid-solid coupling surface. Apply pressure zero on the top of the fluid, on the left and right edge of the pump body simple restraint is applied. Select the asymmetric method to operate model analysis, the first and the second vibration modes are shown in Fig. 3. The first-order harmonic frequencies of the large-size pump and the small-size pump are 368 and 455 Hz, respectively. The second-order harmonic frequencies of the large-size pump and the small-size pump are 1068 and 1340 Hz, respectively.

4. Experiments: Four kinds of micropumps with different valves and PZT actuators were designed and fabricated. Their performances were tested by frequency sweeping experiments. The performance testing system for the micropumps is shown in Fig. 4. The Sinusoidal AC signal from the signal generator (Tektronix AFG3022) is magnified 15 times by a PZT drive power supply (HPV piezo driving source, China), and then drives

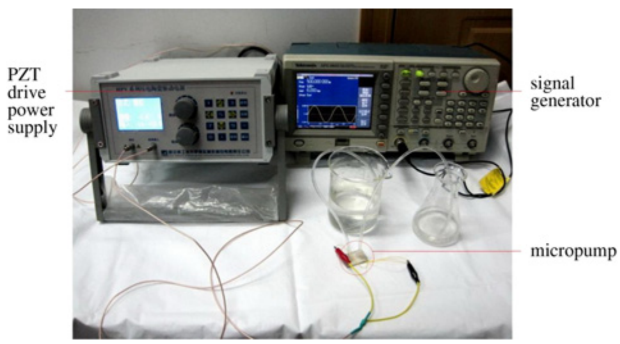

Figure 4 *Testing system of the assembled pumps*

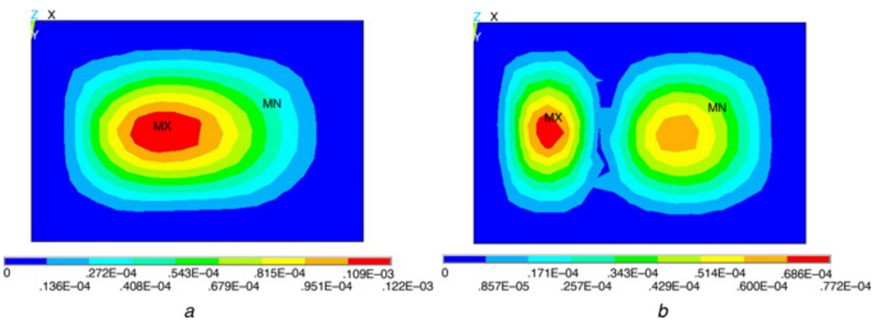

Figure 3 *Vibration modes of the pump body*
a First-order vibration mode
b Second-order vibration mode

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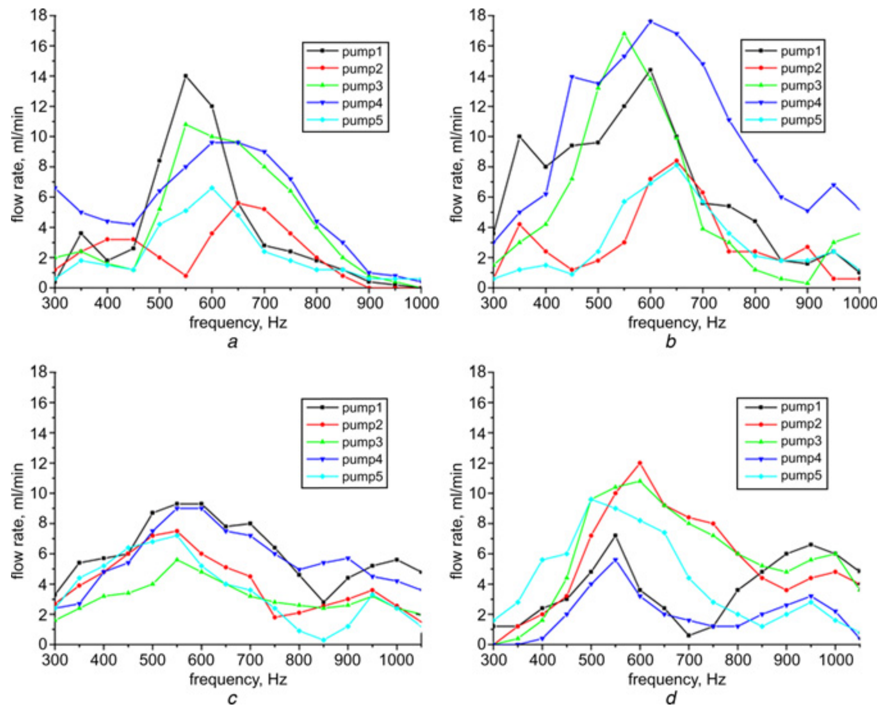

Figure 5 *Flow rate–frequency curves of the four kinds of micropumps*
a Large-size micropumps with three-beam valves
b Large-size micropumps with five-beam valves
c Small-size micropumps with three-beam valves
d Small-size micropumps with five-beam valves

the bimorph to actuate the pump. The drive force of the bimorph is adjusted by the frequency and amplitude of the sinusoidal signal.

The frequency sweeping experiments were conducted to discover the optimum working frequency. The testing frequency was from 300 to 1000 Hz in steps of 50 Hz, and the sinusoidal signal voltages applied on the small-size pump and large-size pump were 210 V (peak–peak) and 270 V (peak–peak), respectively. The back pressure applied on the micropumps was zero, and the liquid used in the experiments was deionised water. The experimental results are shown in Fig. 5.

5. Results and discussion: Fig. 5 shows that two or three peaks of the flow rates of the micropumps emerge with increasing of the frequency. The peak frequencies of the four kinds of micropumps are shown in Tables 1 and 2, and they are the average for each kind of micropump.

With respect to the large-size micropump with three-beam valves, when the actuation frequency was low, the amplitude at the centre of the membrane was low, hence the flow rate was correspondingly low. Then, with increase of the frequency, the flow rate increased correspondingly, when the frequency reached the first-order harmonic frequency of the pump body, the amplitude of the membrane reached a peak, therefore the flow rate reached a peak. Then, the actuation frequency reached 600 Hz, the amplitude of the membrane reached the highest value, because the frequency is close to the harmonic frequency of the PZT bimorph. Meanwhile, the valves worked perfectly, so the flow rate reached the maximum value. Afterwards, it decreased with continuous increase of the frequency. However, as to the large-size micropump with five-beam valves, the flow rate appeared at peak again when the frequency reached 950 Hz which is close to the harmonic frequency of the five-beam valve in water, since the valves worked perfectly, it had no negative influence on liquid flow.

With respect to the small-size micropump with three-beam valves, the first peak of the flow rate appeared at about 550 Hz which is close to the first-order harmonic frequency of the pump and the first-order harmonic frequency of the three-beam valve in water. Then, the frequency reached close to the harmonic frequency of the PZT bimorph, but it is also close to the second-order harmonic frequency of the pump body. The second-order vibration mode of the pump body has a negative effect on the drive, hence the flow rate appeared at peak, but it was lower than the first one. For the small-size micropump with five-beam valves, the first peak of flow rate appeared at about 550 Hz which is close to the first-order harmonic frequency of the pump. Then, the frequency reached about 950 Hz which is close to the harmonic frequency of the five-beam valve in water, and the second peak of the flow rate appeared. Similar to the small-size micropump with three-beam valves, the second peak was lower than the first peak.

We can conclude that the optimum working frequencies of the pumps appear at the harmonic frequencies of the vibrating parts. The centre displacement of the membrane has a greater influence than the valves, so the PZT bimorph has the greatest influence on the flow rate. However, the second-order vibration mode of the pump body has a negative influence on the drive, therefore it would be better to keep the harmonic frequency of the PZT bimorph far away from the second-order harmonic frequency of the pump body.

Table 1 Optimum working frequencies of the large-size micropumps

Shape of valves	Peak frequencies of the flow rates		
three-beam valve	about 350 Hz	about 600 Hz	/
five-beam valve	about 350 Hz	about 650 Hz	about 950 Hz

Table 2 Optimum working frequencies of the small-size micropumps

Shape of valves	Peak frequencies of the flow rates	
three-beam valve	about 550 Hz	about 950 Hz
five-beam valve	about 550 Hz	about 950 Hz

The optimum working frequencies for each kind of the four different pumps are of the same tendency but not of the same value, and the experimental results are not exactly coordinated with the simulation results. The main reasons are as follows: (i) the depths of the pump chamber were not the same because of the machining error of the pump body and different thicknesses of the adhesive layer; (ii) the bimorph beam length has a great effect on the resonant frequency, when the bimorph was fixed on the micropump by glue, the beam lengths were not the same; and (iii) the water depth on both sides of the valve affects its harmonic frequency.

6. Conclusions: Polymeric check valve micropumps actuated by the PZT bimorph were studied in this Letter. There were two sizes of pump bodies and PZT bimorphs as well as two kinds of valves. The vibration characteristics of the vibrating parts were simulated by the FEM method, and the performances of these micropumps were tested by frequency sweeping experiments. The experimental results approximately agree with the simulation results. The optimum working frequencies of the pumps appear at the harmonic frequencies of the vibrating parts, and the PZT bimorph has the greatest influence on it. This research could serve as a theoretical and experimental basis for the design and optimisation of polymeric micropumps.

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