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Effects of Driving Mode on the Performance of Multiple-Chamber Piezoelectric Pumps with Multiple Actuators

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Abstract: Due to the limited output capability of piezoelectric diaphragm pumps, the driving voltage is frequently increased to obtain the desired output. However, the excessive voltage application may lead to a large deformation in the piezoelectric ceramics, which could cause it to breakdown or become damaged. Therefore, increasing the number of chambers to obtain the desired output is proposed. Using a check-valve quintuple-chamber pump with quintuple piezoelectric actuators, the characteristics of the pump under different driving modes are investigated through experiments. By changing the number and connection mode of working actuators, pump performances in terms of flow rate and backpressure are tested at a voltage of 150 V with a frequency range of 60 Hz –400 Hz. Experiment results indicate that the properties of the multiple-chamber pump change significantly with distinct working chambers even though the number of pumping chambers is the same. Pump performance declines as the distance between the working actuators increases. Moreover, pump performance declines dramatically when the working piezoelectric actuator closest to the outlet is involved. The maximum backpressures of the pump with triple, quadruple, and quintuple actuators are increased by 39%, 83%, and 128%, respectively, compared with the pump with double working actuators; the corresponding maximum flow rates of the pumps are simply increased by 25.9%, 49.2%, and 67.8%, respectively. The proposed research offers practical guidance for the effective utilization of the multiple-chamber pumps under different driving modes.

Keywords: piezoelectric pump, multiple chambers, multiple actuators, driving mode, flow rate, backpressure

1 Introduction

Micropumps are becoming increasingly important for a wide range of applications, such as, pharmaceutical and bio-medical drug delivery systems, serving as micro-fluid flow control appliance for analyzing systems for chemical and biological substances[1–3]. Because micropumps have the unique ability to deliver an accurate amount of liquid, many different types of micropumps have been developed using several actuation methods such as, electrostatic, piezoelectric, thermopneumatic, electrochemical, shape memory alloy(SMA), and electromagnetic[4]. Among the various kinds of working principles, piezoelectric actuation is promising due to its relatively simple structure, low cost, short response time, good reliability and low power consumption[4]. Furthermore, piezoelectric actuation is the first actuation principle used for micropumps[5]. Unsurprisingly, a large number of papers on piezoelectric actuation for micropump applications have been published. Research and development on piezoelectric pumps have made considerable progress in the last three decades. VALDOVINOS, et al[6], developed a piezohydraulic pump used in pulsatile pediatric ventricular assist devices. LENG, et al[7], presented a spiral-tube-type valveless piezoelectric pump with gyroscopic effect. TANAKA[8] used a very flexible and ultra-thin glass sheet to realize a peristaltic pump installed on an entirely glass-based microchip. HU, et al[9], developed a piezoelectric-stack pump with variable-cross-section oscillating vibrator. ZHANG, et al[10], proposed a piezoelectric micropump with an integrated sensor based on space-division multiplexing.

The classic piezoelectric pump consists of a pump chamber with a diaphragm(pumping membrane) and two passive check valves. The diaphragm, actuated by a piezoelectric disk glued onto it, generates a stroke volume and causes pressure for suction and discharge flow alternately—just like the pumping principle of the human heart. Although micropumps using piezoelectric actuation have the many advantages herein mentioned, their high operational voltages and small volume stroke are considered disadvantageous[11–12]. Similarly, many studies over the last three decades have been done on piezoelectric pumps with the goal of achieving higher performance at lower actuation voltage. As a result, some optimization of the geometrical design of piezoelectric pumps was investigated[13]. WANG, et al[14–15], introduced a folded

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piezoelectric vibrator and two fixed ends polydimethylsiloxane valves in order to increase the flow rate. HAM, et al[16], presented the design and fabrication of a piezoelectric pump using hinge-lever amplification mechanism. The pump achieved no-load flow rate, maximum output pressure of 600 ml/min, and 6.8 kPa, at the applied voltage of 100 V. LI, et al[17], developed a robust, passive high-frequency high-pressure micro check valve for piezoelectrically actuated pumps. Integrated with a compact piezoelectric pump, the microvalve could produce a pressure of 2.4 MPa at 10 kHz frequency. Because further enhancement of the single-chamber pump performance was limited, piezoelectric pumps with double or even multiple actuators and chambers were successfully proposed and developed. ULLMANN[18] analyzed the performance of one single-chamber and one double-chamber piezoelectric valveless pumps, and found that the double-chamber pump yielded a significant improvement over its single chamber counterpart. Two serial- and parallel-connection valveless piezoelectric pumps were then fabricated in the study. The performance characteristics of the different combinations were reported and critically evaluated[19]. ZHANG, et al[20], developed a double-actuator piezoelectric pump with flow rate self-sensing capability. KIM, et al[21], investigated the effect of phase shift on optimal operation of serial-connected double-chamber valveless micropumps. KAN, et al[22], proposed a serial-connection quadruple-chamber piezoelectric pump with cantilever valves and verified through experiment results that the flow rate and backpressure of the serial-connection multiple-chamber pumps had increased with the increase in the number of pump chambers. So far, in the author's best knowledge, relatively little research has been performed on the multiple-chamber and multiple-actuator piezoelectric pumps.

In this paper, the effects of driving mode on the performance of multiple-chamber piezoelectric pumps with multiple actuators are studied through experiment. In the study, the driving mode mainly referred to the connection mode and actuated sequence of the piezoelectric actuators. KAN, et al[22], verified that the chamber number had an influence on multiple-chamber pump performance. However, in the results of the present study, properties of the multiple-chamber pump changed significantly with different working chambers even though the number of pumping chambers was the same. In another sense, these results mean that the multiple-chamber pump is able not only to produce robust liquid propulsion at low energy consumption, but also offer a high level of flexibility in terms of flow rate and backpressure. Through basic experiments on frequency characteristics, the effects of driving mode on the output characteristics of the multiple-chamber and multiple-actuator pump were investigated. This work is beneficial in that, it offers a thorough understanding of the working properties of multiple-chamber pumps, making improvement of those working properties possible. Moreover, it demonstrates how to utilize multiple-chamber pumps effectively and how to adjust their optimal performance according to different application requirements. This study was also expected to explore a new way to control pumping rate and pressure, which could be achieved by changing the working modes of multiple-chamber pumps rather than the driving voltages. This technique would be especially suitable in a situation where the voltage amplitude cannot be adjusted.

2 Structure and Working Principle of the Multiple-Chamber Pump

The multiple-chamber and multiple-actuator pump in the present work consists of five piezoelectric diaphragms used as actuators, six check valves, five pump chambers, a pump body, an inlet, and an outlet (Fig. 1).

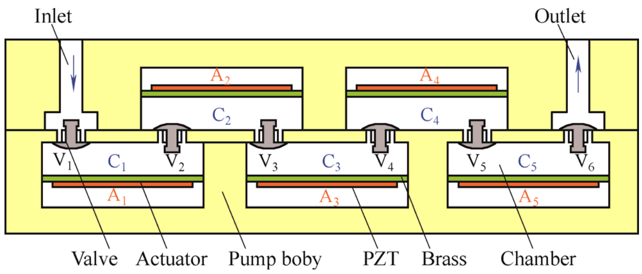

Fig. 1. Structural schematic diagram of the multiple-chamber piezoelectric pump with multiple actuators

In Fig. 1, A_i (i=1, 2,⋯, 5), C_j (j=1, 2,⋯, 5), and V_k (k=1, 2,⋯, 6), are the actuators, chambers, and check valves, respectively. The five piezoelectric actuators, which are the core components of the pump, are from commercial circular diaphragms produced by Murata Manufacturing Co., Ltd. The main parameters of the circular diaphragm are listed in Table 1.

Table 1. Main parameters of the piezoelectric diaphragm

Part type	Brass diameter Φ_m/mm	Element diameter Φ_p/mm	Electrode diameter Φ_e/mm	Diaphragm thickness T_d/mm	Brass thickness T_m/mm
7BB-35-3	35.0	25.0	23.0	0.53	0.3

The pump body is made of polymethyl methacrylate (PMMA) which has advantageous properties of easy processing, light weight, insulation, and easy observation. The six umbrella-shaped check valves made of rubber are used to separate the chambers. The structural form of the multiple-chamber pump can be simply described as: the inlet and the outlet of the five single-chamber pumps are connected serially and separated by the check valves. The prototype pump with the dimensions 170 mm×50 mm×20 mm is shown in Fig. 2.

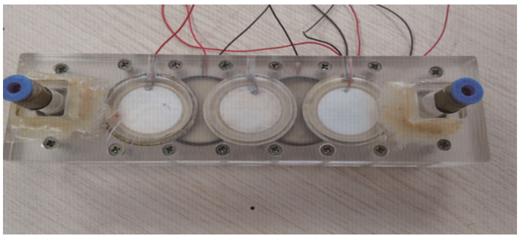

Fig. 2. Photograph of the multiple-chamber piezoelectric pump

Fig. 3 shows the working principle of the serial-connection multiple-chamber piezoelectric pump when all the actuators are operating. The asynchronous operation mode of working piezoelectric actuators is needed in order to make the serial-connection pump run more efficiently. The phase difference of driving voltages between the working actuators near the border is 180°; that is, the diaphragm actuators of the pumping chambers near the border are operating in an anti-phase mode[22]. In response, the adjacent working actuators generate opposed deflection, which results in the increase of one chamber volume and the decrease of the next chamber volume. When the pump chamber volume becomes enlarged, an underpressure is generated in the chamber and fluid flows into the chamber through the inlet valve(Fig. 3(a)). When the pump chamber volume is reduced, an overpressure is generated in the chamber and the fluid flows through the outlet valve(Fig. 3(b)). When alternating voltage is applied to the piezoelectric actuators, the diaphragms are actuated to produce bending deformation, which then causes volume change in pump chambers alternately. Working fluid is drawn into the pump chamber during the chamber expansion/suction stroke and forced out of the pump chamber during the contraction/discharge stroke. As a result, the working fluid is continuously delivered from one chamber to the next. The liquid is then moved from the inlet to the outlet of the multiple-chamber pump. Note that this case, that all the actuators are simultaneously working, was only taken as an example to demonstrate the working principle of the multiple-chamber pump. In reality, the multiple-chamber pump can move working fluid only when there is at least one working actuator, in which case, the chamber with the inactive actuator is equivalent to the fluidic channel. When more than two piezoelectric actuators are working, piezoelectric actuators of the pumping chambers near the border will be operated in an anti-phase mode. Otherwise, the pump can not possibly move the fluid. For example, when the first two actuators of A_1 and A_2 are at work and operated in an in-phase mode, the middle valve V_2 will not work and become a load. This paper mainly studies the dynamic performance of the multiple-chamber pump with various combinations of multiple driving chambers, in terms of flow rate and backpressure.

3 Experimental Setup

To explore the characteristics of the multiple-chamber and multiple-actuator pump under different driving modes, pump performance in terms of flow rate and backpressure needs to be tested. The overall arrangement of the testing apparatus is illustrated in Fig. 4.

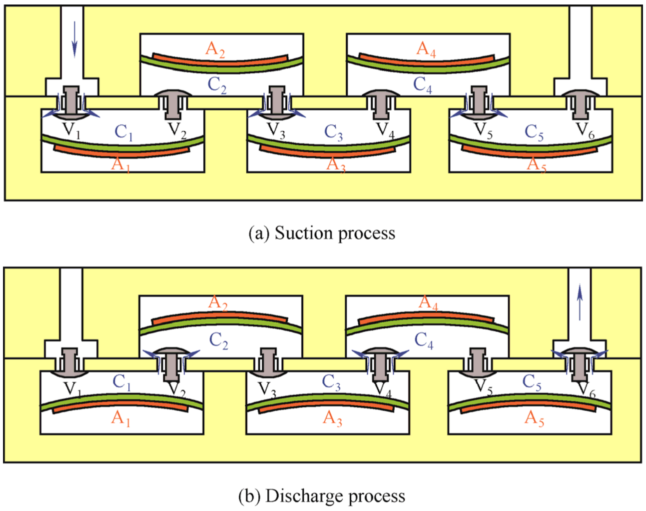

Fig. 3. Working principle of serial-connection multiple-chamber piezoelectric pump

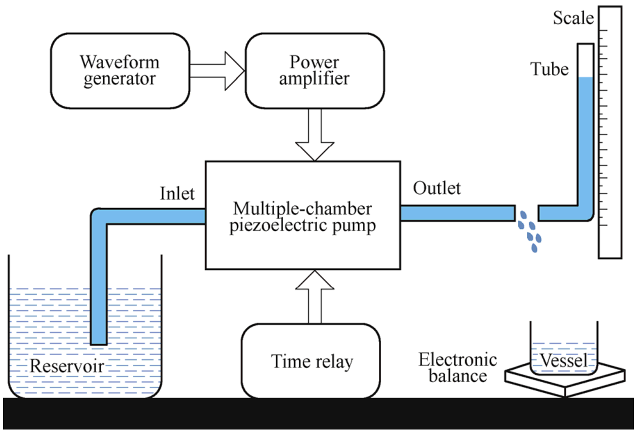

Fig. 4. Experimental setup

Tap water at room temperature, as the best representative of working fluid, was used as working medium. A large reservoir ensured a constant height and a constant inlet pressure during the measurement. The inlet and outlet of the pump were connected to the liquid reservoir by plastic tubes. A digital PZT power supply(SANKI, P211) was used to drive the piezoelectric pump. The power supply could provide a variable frequency of 60-400 Hz and an AC voltage range of 0-240 V. An electronic balance(Ohaus, CP1502C) was used to measure the flow rate. The main technical parameters of the balance are as follows: a measurement range of 1510 g, a division value of 0.01 g and a repeatability of 0.01 g. According to the energy equation[23], the water column height which was perpendicular to the water free surface was measured by a scale ruler in order to obtain the pumping pressure value. A time relay was used to set the time interval to achieve the average flow rate and the time interval of sixty seconds was set in each measurement. The resulting mass that would be measured by the balance was the value of the average flow per minute. Using this setup, a series of experiments were conducted at a fixed driving voltage of 150 V and in a maintained frequency range from 60 Hz to 400 Hz to obtain the effects of driving mode on the performance of the multiple-chamber piezoelectric pump with multiple actuators.

4 Experiments

Generally, flexibility, in terms of pumping flow rates, increases as the number of chamber increases. The quintuple-chamber pump in this study could run in modes from a single actuator to quintuple actuators, according to different application requirements. Because this paper focuses on the effects of driving mode on the performance of multiple-chamber piezoelectric pumps, the study of the pump with more than two working actuators was mainly carried out here. In any case, the number of actual working actuators represents the number of chambers for this multiple-chamber pump. Then, we successively tested the output characteristics of the pump with different working piezoelectric actuators, paying special attention to the pump with the same number of chambers and different positions of working actuators.

4.1 Results for the pump with double actuators

To carry out this experiment, every two piezoelectric actuators of the pump needed to be simultaneously connected with the sinusoidal AC power. Moreover, the double actuators needed to be operated in the asynchronous mode, thereby forming ten serial-connection double-chamber(double-actuator) piezoelectric pumps were one after another. While adjusting actuation frequency gradually, the flow rate(ml/min) versus frequency(Hz) characteristics of the double-chamber pumps were first tested at a fixed driving voltage of 150 V. Fig. 5 shows the resulting double-chamber pump performance in terms of flow rate versus actuation frequency.

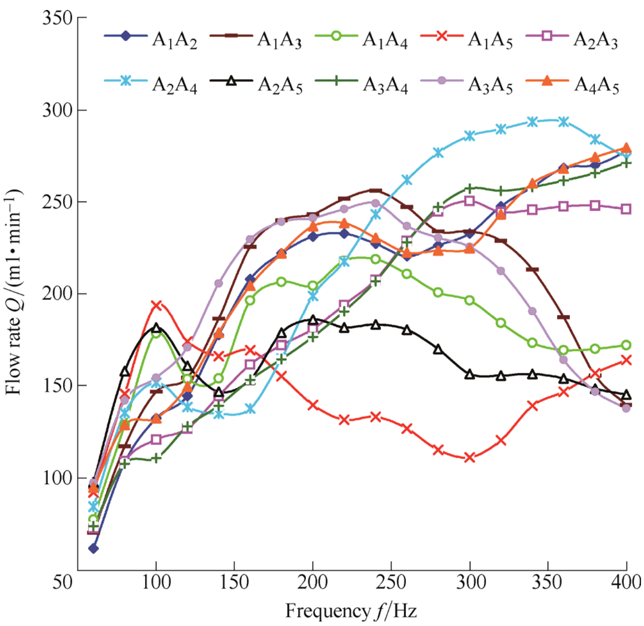

Fig. 5. Flow rate versus actuation frequency of the pump with double actuators at a driving voltage of 150 V

On one hand, the performances of ten double-chamber pumps vary significantly from two different working actuators. On the other, the flow rate versus frequency curve of the pump with A_1/A_2 working almost coincides with that of the pump with A_4/A_5 working. The flow rate increases with the frequency within almost the entire range from 60 Hz to 400 Hz. The maximum flow rate of 279.6 ml/min is measured at 400 Hz and at a driving voltage of 150 V. Something similar occurs when A_2/A_3 and A_3/A_4, as well as A_1/A_3 and A_3/A_5, are at work. Moreover, when the frequency is smaller than 260 Hz, there is no remarkable performance difference between the pumps with A_1/A_2, A_1/A_3, A_3/A_5, and A_4/A_5 working. As results show, the flow rate versus frequency curves of the pump with A_1/A_4, A_1/A_5, and A_2/A_5 working are also very coincidental when the frequency is smaller than 120 Hz. All three curves reach their peak at the frequency of 100 Hz. Additionally, there remains a similar trend for the two curves with A_1/A_4 and A_2/A_5 working even though the frequency is greater than 120 Hz.

The above-described experiments preliminarily display the characteristics of the pump with different double actuators. To continue, because the serial-connection pumps could be very helpful in improving backpressure and flow rate, the backpressure versus frequency characteristics of the double-chamber pumps were also tested. After transforming the measured water column height into the pressure value, the results are obtained. Fig. 6 shows the resulting double-chamber pump performance in terms of backpressure versus actuation frequency, at a fixed driving voltage of 150 V. It is observed that the backpressure versus frequency curves of the pump with A_1/A_2, A_2/A_3, A_2/A_4, and A_3/A_4 working are similar within the whole frequency range. In these situations, the pump achieves a maximum backpressure of 7.05 kPa at around 140 Hz to 160 Hz and then shows a relatively good backpressure stability when the frequency is greater than 180 Hz. The curve with A_1/A_3 working is also similar to the configurations mentioned above when the frequency is smaller than 240 Hz. Other curves in the experiment show relatively big backpressure fluctuation, especially when A_5 actuator is involved.

4.2 Results for the pump with triple actuators

In this section and the two that follow, the experiment procedures are basically the same with the procedure used for the pump with double actuators, except that the number of piezoelectric actuators connected simultaneously with the power supply are three, four, and five, respectively. Moreover, it is noted that the piezoelectric actuators of the pumping chambers near the border are operated in an anti-phase mode. When three piezoelectric actuators were simultaneously connected with the power supply in turn, ten serial-connection triple-chamber piezoelectric pumps were also formed. Figs. 7 and 8 show the experiment results for the performance of the ten triple-chamber pumps in terms of flow rate and backpressure versus actuation frequency, respectively. In contrast with the earlier discussed double-chamber pumps, although the flow rate increases modestly, the backpressure of the triple-chamber pumps increases significantly.

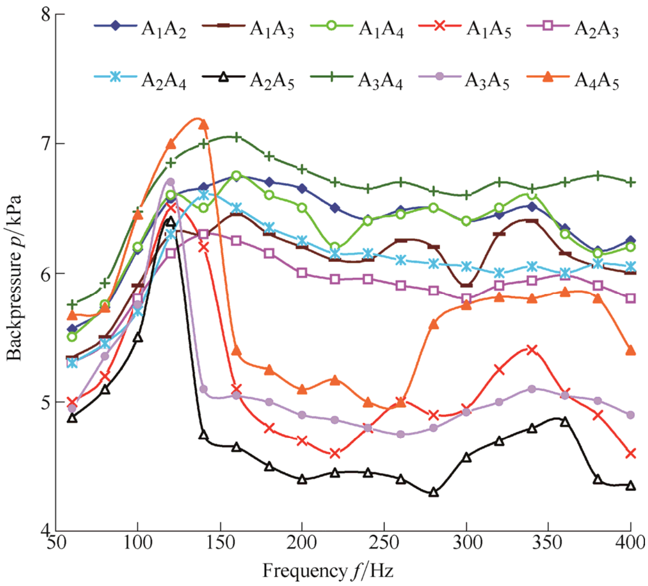

Fig. 6. Backpressure versus actuation frequency of the pump with double actuators at a driving voltage of 150 V

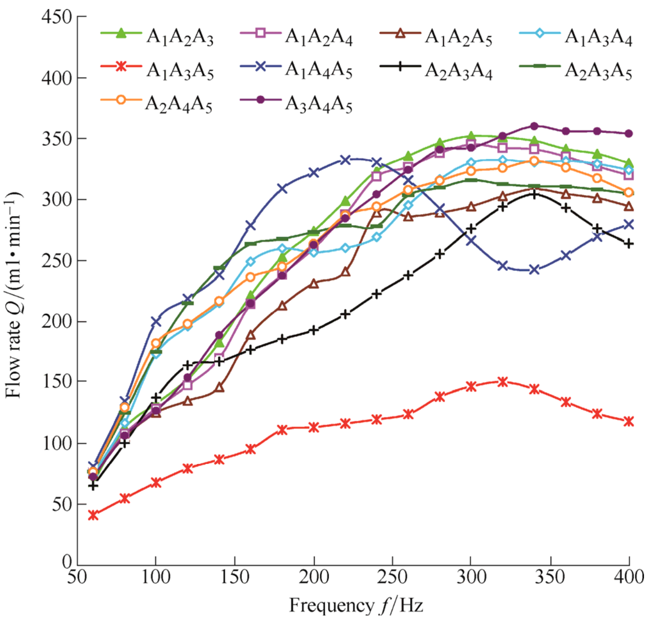

Fig. 7. Flow rate versus actuation frequency of the pump with triple actuators at a driving voltage of 150 V

In the experiment, after the flow rate-frequency characteristic of the pump with $A_1/A_2/A_3$ working is tested, the flow rate decreases slightly with A_4 substituting for A_3. The maximum flow rate decreases from 352 ml/min to 345.2 ml/min. The decrease of the flow rate becomes more obvious when A_5 is substituted for A_3, wherein the maximum flow rate decreases from 352 ml/min to 308.4 ml/min. Furthermore, the flow rate of the pump with $A_1/A_3/A_5$ working decreases sharply when A_5 is substituted for A_2, wherein the maximum flow rate can reach only up to 150.4 ml/min. In contrast, the flow rate versus frequency curves of the pump with $A_1/A_2/A_3$, $A_1/A_2/A_4$, and $A_3/A_4/A_5$ working are almost coincidental within the whole frequency range. Likewise, the curve of the pump with $A_2/A_3/A_4$ working takes on a similar trend when the frequency is smaller than 120 Hz. Three other curves, those for pumps with $A_1/A_3/A_4$, $A_2/A_3/A_5$, and $A_2/A_4/A_5$ working, also take on a similar trend. Although the curve of the pump with $A_1/A_4/A_5$ working also shows a similar trend when the frequency is smaller than 120 Hz, the flow rate fluctuation becomes slightly big when the frequency is greater than 120 Hz. Fig. 8 demonstrates that most of the ten triple-chamber pumps have similar backpressure versus frequency characteristics. Notably, the maximum backpressure of almost all triple-chamber pumps is achieved at around 120 Hz; for example, a maximum backpressure of 9.8 kPa is recorded at the frequency of 120 Hz for the pump with $A_1/A_2/A_3$ working.

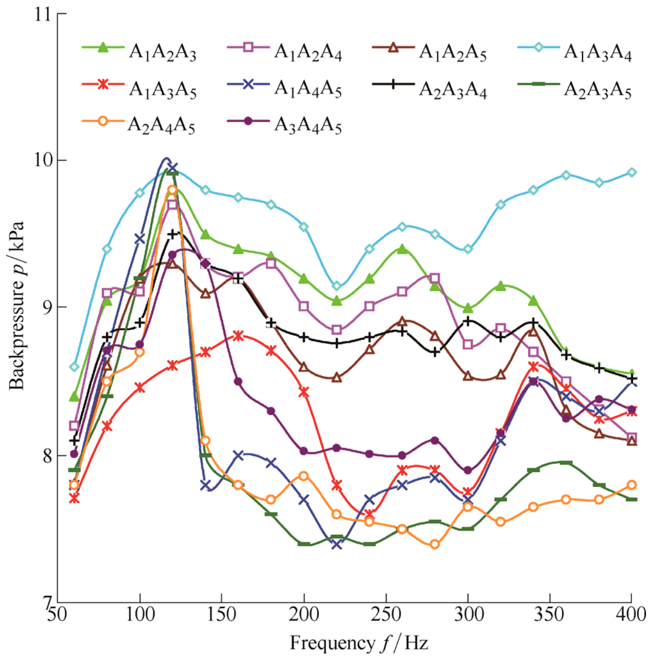

Fig. 8. Backpressure versus actuation frequency of the pump with triple actuators at a driving voltage of 150 V

4.3 Results for the pump with quadruple actuators

In this section, the experiment results involving the pump with quadruple actuators are immediately presented because the experiment procedures applied are very similar to the previously discussed experiments. Figs. 9 and 10 show the experiment results for the performance of the five quadruple-chamber pumps in terms of flow rate and backpressure versus actuation frequency, respectively. In contrast with the triple-chamber pumps, although the flow rate of the quadruple-chamber pumps increases moderately, the backpressure increases significantly. The maximum backpressure reaches 12.9 kPa at an actuation frequency of 100 Hz, which is about 1.31 and 1.91 times larger than that of the triple-chamber pump with $A_1/A_2/A_3$ working and the double-chamber pump with A_1/A_2 working, respectively.

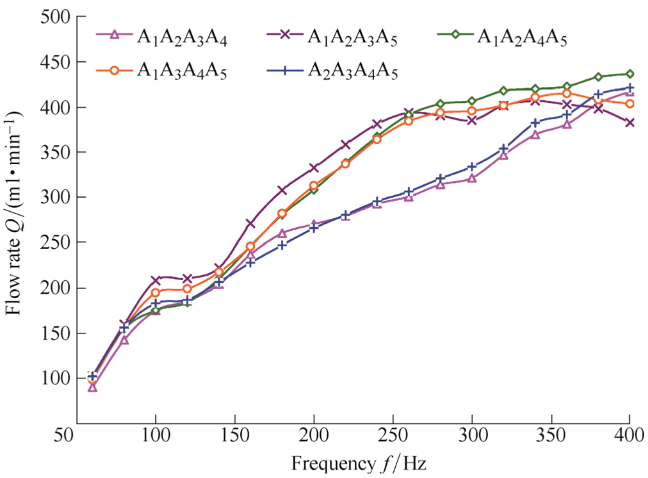

Fig. 9. Flow rate versus actuation frequency of the pump with quadruple actuators at a driving voltage of 150 V

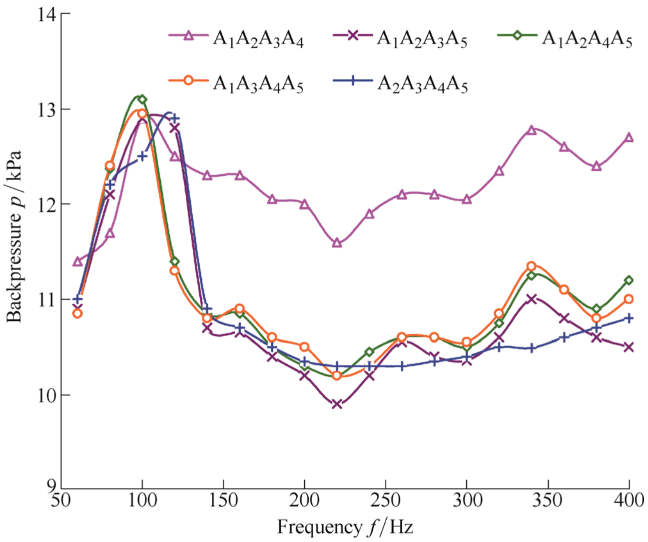

Fig. 10. Backpressure versus actuation frequency of the pump with quadruple actuators at a driving voltage of 150 V

Fig. 9 demonstrates that, in general, the flow rate of all the five quadruple-chamber pumps increases with the frequency. Moreover, the five flow rate-frequency curves are very similar when the frequency is smaller than 140 Hz. Specifically, within the whole frequency range, the flow rate versus frequency curve of the pump with $A_1/A_2/A_3/A_4$ working almost coincides with the curve of the pump with $A_2/A_3/A_4/A_5$ working. The pump achieves a maximum flow rate of 417.2 ml/min at the actuation frequency of 400 Hz. The pump also displays very similar characteristics when $A_1/A_2/A_3/A_5$ or $A_1/A_3/A_4/A_5$ are working. Furthermore, the flow rate-frequency curve of the pump with $A_1/A_2/A_4/A_5$ working almost coincides with those two curves when the frequency is smaller than 260 Hz. However, Fig. 10 demonstrates that the pump with $A_1/A_2/A_3/A_4$ working has relatively good frequency stability; its backpressure versus frequency characteristics are the best compared with the four other quadruple-chamber pumps. The backpressure versus frequency curves of the five quadruple-chamber pumps are very similar when the frequency is smaller than 100 Hz. When the frequency is greater than 100 Hz, however, except for the curve with $A_1/A_2/A_3/A_4$ working, the other four curves display a big decline in the backpressure. This infers that the performance of the quadruple-chamber pump becomes poor when the A_5 actuator next to the outlet is involved.

4.4 Results for the pump with quintuple actuators

In this situation, it would be useless to experiment on the effects of driving mode on the multiple-chamber pump because all the piezoelectric actuators would take part in running the pump. At the same time, this situation represents the maximum work ability of the serial-connection multiple-chamber pump under this kind of driving mode. To demonstrate the performance of the quintuple-chamber pump and to compare it with the previously discussed pumps with different driving modes, frequency characteristics were herein also tested. Similarly, the experiment results for the serial-connection quintuple-chamber pump are immediately presented. Figs. 11 and 12 show the experiment results for the performance of the quintuple-chamber pump in terms of flow rate and backpressure versus actuation frequency, respectively.

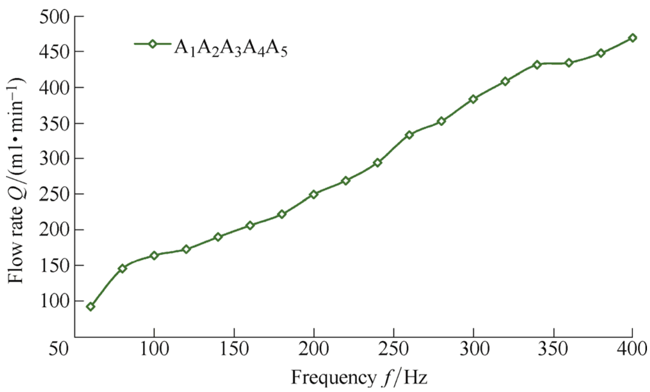

Fig. 11. Flow rate versus actuation frequency of the pump with quintuple actuators at a driving voltage of 150 V

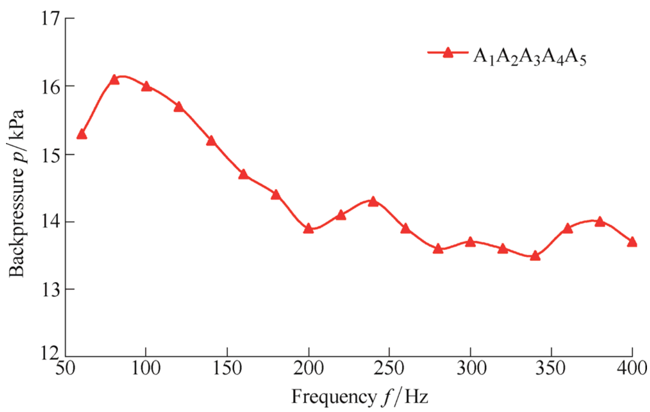

Fig. 12. Backpressure versus actuation frequency of the pump with quintuple actuators at a driving voltage of 150 V

Unlike with the quadruple-chamber pumps, the flow rate of the quintuple-chamber pump increases slightly. However, the backpressure increases significantly. As demonstrated in Fig. 11, the increase of the flow rate with the frequency is nearly linear within the whole frequency range from 60 Hz to 400 Hz. The pump achieves a maximum flow rate of 469.2 ml/min at the actuation frequency of 400 Hz, which is approximately 1.12, 1.33, and 1.68 times larger than that of the quadruple-chamber, triple-chamber, and double-chamber pumps, respectively. In Fig. 12, however, results show that the backpressure obviously increases with the number of chambers. The maximum backpressure reaches 16.1 kPa at an actuation frequency of 80 Hz, which is about 1.25, 1.64, and 2.39 times larger than that of the quadruple-chamber pump with $A_1/A_2/A_3/A_4$ working, the triple-chamber pump with $A_1/A_2/A_3$ working, and the double-chamber pump with A_1/A_2 working, respectively.

5 Discussion

As the previously discussed experiments describe, the performance of a multiple-chamber piezoelectric pump is mainly studied using various combinations of multiple-chamber actuation. Experiment results show that as the combinations of driving chambers change, pump performance changes in terms of flow rate and backpressure. Moreover, both flow rate and backpressure vary remarkably with different actuation chambers even if the number of driving chambers is same. There is no denying the difference between the piezoelectric actuators even though these five actuators come from one production batch. The actuator's difference is just the one of the possible reasons. For the multiple-chamber pump, the opening and closing movement of the middle valves are caused by the simultaneous changing of liquid pressure in the two actuation chambers near the border(one actuation chamber pushes and the other pulls). In the check-valve piezoelectric pumps, the pull capability of the actuation chamber is weaker than its push capability; this characteristic of the actuation chamber is the main reason why the dynamic performance of the multiple-chamber pump changes significantly with different actuation chambers. When the working actuators are close to the inlet, the idle check valves are opened through the relatively strong push capacity. Meanwhile, the idle check valves are opened through the relatively weak pull capability when the working actuators are close to the outlet. Evidently, the idle check valves have completely become loads even though fluid and backpressure transmission can also be achieved in the non-working chambers.

The check efficiency of check valves becomes another important factor that influences the working properties of multiple-chamber pumps with different actuation chambers. The check efficiency denoted by η is defined as[24–26]

$$\eta = \frac{\Delta p_{\mathrm{neg}}(\bar{u}_{\mathrm{throat}})}{\Delta p_{\mathrm{pos}}(\bar{u}_{\mathrm{throat}})}, \tag{1}$$

or

$$\eta = \frac{V_{\mathrm{t}} - V_{\mathrm{m}}}{V_{\mathrm{t}}}, \tag{2}$$

where Δp_{neg}—Pressure loss in negative flowing direction,
Δp_{pos}—Pressure loss in positive flowing direction,
V_{t}—Theoretical discharge volume,
V_{m}—Back-flow volume per cycle.

According to Refs. [24]–[26], the pressure loss is denoted as

$$\Delta p(\bar{u}_{\mathrm{throat}}) = \frac{1}{2}\xi\rho\bar{u}_{\mathrm{throat}}^2, \tag{3}$$

where $\bar{u}_{\mathrm{throat}}$—Velocity calculated over the narrowest (or throat) cross-section,
ρ—Fluid density,
ξ—Loss coefficient dependent on the conduit geometry and the flowing direction.

Check efficiency is not merely relevant to the above-mentioned parameters. The phase shift(φ, between the movement of the valve and actuator) has great influence on check efficiency as well, because opening/closing of the passive check valves always lags behind the vibration of the piezoelectric actuators[22, 27]. The check efficiency decreases when the phase shift increases($\eta \propto 1/\varphi$). When the multiple-chamber pump runs in various driving modes, the difference in relative distances between the working actuator and the check valves will directly result in a difference in the phase shift, which makes the check efficiency of the valves differ from each other. Therefore, the check efficiency of check valves further influences the characteristics of the pump even if the number of working chambers is same, as demonstrated in the experiments.

Results show that backpressure is significantly different when driving modes are changed, and doubles with the number of pumping chambers, leading to a wide variety of fluid compressibility. Therefore, the fluid compressibility also has a great effect on pump performance. The bulk modulus of the fluid is a reciprocal of the compressibility, and is given as[28–29]

$$\beta_{\mathrm{e}} = -V_{\mathrm{o}}\frac{\Delta p}{\Delta V}, \tag{4}$$

where β_{e}—Bulk modulus of the fluid,
ΔV—Volume change of pump chamber,
p—Pressure generated in the chamber before the liquid is discharged,
V_{o}—Original chamber volume.

The negative sign denotes that volume decreases with a corresponding increase in pressure. Given the liquid beginning to be discharged from chamber at pressure p and not being compressed further, the total volume displacement ΔV_{out} of pump chamber depends mainly on the pressure p[30–31]:

$$\Delta V_{\text{out}} \approx \frac{\pi s_{11}^E(1-\upsilon_p)(7+\upsilon_p)(1+\alpha\zeta)\mathrm{R}^6}{16h_p^3[3(1-\alpha^2\zeta)^2-4(1+\alpha\zeta)(1+\alpha^3\zeta)]}\bullet \left[\frac{24h_p d_{31}\alpha\zeta(1+\alpha)}{s_{11}^E R^2(1-\upsilon_p)(7+\upsilon_p)(1+\alpha\zeta)}U-p\right]= \frac{3\pi d_{31}R^4}{2h_p^2}\lambda_V U\left(1-\frac{p}{p_g}\right), \tag{5}$$

where p_g—Maximal liquid pressure generated by piezoelectric actuator under an applied voltage,

$$p_g=\frac{24h_p d_{31}\alpha\zeta(1+\alpha)}{s_{11}^E R^2(1-\upsilon_p)(7+\upsilon_p)(1+\alpha\zeta)}U,$$

$$\lambda_V=\frac{\alpha\zeta(1+\alpha)}{3(1-\alpha^2\zeta)^2-4(1+\alpha\zeta)(1+\alpha^3\zeta)},$$

$$\zeta=\frac{s_{11}^E E_m(1-\upsilon_p^2)}{1-\upsilon_m^2},$$

s_{11}^E—Elastic compliance coefficient of piezo-disk,
E_{m}—Elastic modulus of metal plate,
υ_p—Poisson's ratios of piezo-disk,
υ_{m}—Poisson's ratios of metal plate,
α—Thickness ratio of metal plate to piezo-disk, $\alpha=h_m/h_p$,
R—Radius of the actuator (pump chamber),
d_{31}—Piezoelectric strain coefficient,
U—Applied voltage.

Thereby, the net liquid volume ΔV_{net} discharged from the pump chamber is obtained as

$$\Delta V_{\text{net}}=\Delta V_{\text{out}}-\Delta V= \frac{3\pi d_{31}R^4}{2h_{\text{p}}^2}\lambda_V U\left(1-\frac{p}{p_{\text{g}}}\right)-\frac{pV_{\text{o}}}{\beta_{\text{e}}}. \tag{6}$$

Eq. (6) indicates that the net liquid discharged from the pump chamber will vary with the generated pressure. As mentioned above, the pressure differs greatly with the driving modes of the pump. As a result, the driving modes make a huge difference in the pump characteristics because of differences in fluid compressibility. In conclusion, many complicated factors influence the performance of multiple-chamber pumps. The effects of driving mode on the performance of multiple-chamber piezoelectric pumps must be researched and tried through experiment to further form a set of effective theories to characterize multiple-chamber pumps.

In addition, analysis of the frequency characteristics in terms of flow rate and backpressure of double-actuator pumps shows that pump performance worsens as the distance between two working actuators increases. Moreover, pump performance is better when actuators close to the inlet, rather than the outlet, are working. The similar thing happens to pumps with three working actuators. It is found that the output backpressure decreases as the distance between the working actuators increases; and the degradation becomes increasingly evident as the working piezoelectric actuators become closer to the outlet. The possible explanation for these results is that the middle idle check valves consume power when the working piezoelectric actuators are separate, which is not beneficial for power accumulation. Consequently, when all the working piezoelectric actuators are not neighboring, the performance of the pump with $A_1/A_3/A_5$ working is the worst. Moreover, it is found that the double-, triple-, and quadruple-chamber pump's performance becomes poor when the A_5 of the actuator next to the outlet is involved. Further investigations and discussions are needed to adequately explain this phenomenon. However, from the experiments in this study, we could draw the preliminary conclusion that the driving mode of neighboring working actuators close to the inlet is adopted as far as possible when not all the piezoelectric actuators are working.

Compared with the pump having double working actuators, the maximum backpressures of the pump with triple, quadruple, and quintuple actuators are increased by 39%, 83%, and 128%, respectively. The corresponding maximum flow rates are simply increased by 25.9%, 49.2%, and 67.8%, respectively. The column diagram in Fig. 13 is used to present the change visually. The flow rate does not increase efficiently with the increase in number of chambers. This indicates that the main factor that influences flow rate of the serial-connection multiple-chamber pumps is not the number of chambers but the actuation frequency. The main reason being, the number of check valves increases when the number of chambers is increased. However, the output backpressure could be significantly improved by the method used for constructing the serial-connection multiple-chamber pumps. The output backpressure of a multiple-chamber pump is approximate to the sum of the output backpressure of all chambers running individually. The result is generally consistent with that in Ref. [22]. The total backpressure p_{multi} of a serial-connection multiple-chamber pump can be expressed as

$$p_{\text{multi}}=\sum_{i=1}^{n}p_i, \tag{7}$$

where p_i—Pressure generated by single pumping chamber,
n—Chamber number.

According to the relationship between the flow rate and pressure in the hydraulic system, there will be

$$Q=C_v A\sqrt{\frac{2\Delta p}{\rho}}, \tag{8}$$

where Q—Flow rate,
C_{v}—Velocity coefficient,
A—Area of the valve orifice,
ρ—Liquid density,

Δp—Pressure difference.

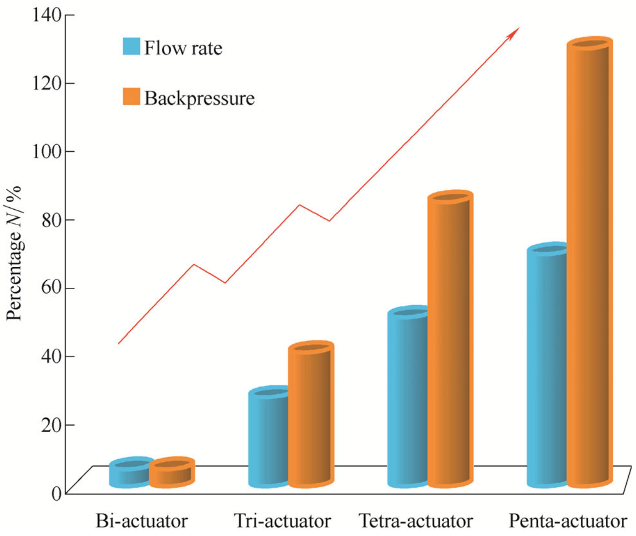

Fig. 13. Increasing rate of backpressure and flow rate of the multiple-chamber pump

Given the same pressure generated by each individual chamber, the total flow rate Q_{multi} of the multiple-chamber pump can be derived as

$$Q_{\text{multi}} = C_{\text{v}} A\sqrt{\frac{2\sum_{i=1}^{n} p_i}{\rho}} = \sqrt{n}Q\,. \tag{9}$$

Accordingly, both Eqs. (7) and (9) may explain why the increase of the backpressure is much greater than that of flow rate as the number of pumping chambers increases. Moreover, the increasing percentages obtained in the flow rate and pressure experiments are consistent with the theoretical calculations in Eqs. (7) and (9), respectively.

6 Conclusions

(1) A serial-connection quintuple-chamber pump with quintuple piezoelectric actuators is fabricated and the effects of driving mode on the performance of the multiple-chamber and multiple-actuator pumps are presented.

(2) The flow rate and backpressure of the pump change with different working chambers. Moreover, the properties of the multiple-chamber pump vary significantly with specific working actuators even though the number of pumping chambers is same. This result means that the multiple-chamber pump is able not only to produce robust liquid propulsion at low energy consumption, but also offer a high level of flexibility in terms of flow rate and backpressure.

(3) The performance of the multiple-chamber pump declines as the distance between the working actuators increases. Likewise, pump performance declines dramatically when the working piezoelectric actuator close to the outlet is involved. This result demonstrates that when five piezoelectric actuators are not necessarily running at the same time for the quintuple-chamber pump, it is optimum to adopt neighboring working actuators closest to the inlet, which should then be operated in an asynchronous mode.

(4) The maximum backpressures of the pump having triple, quadruple, and quintuple actuators increase by 39%, 83%, and 128% respectively, compared with the pump having double working actuators; while the corresponding maximum flow rates simply increase by 25.9%, 49.2%, and 67.8%, respectively. This result indicates that the flow rate and backpressure mainly depend on the actuation frequency and the number of chambers in the multiple-chamber pumps, respectively.

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