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A piezoelectric micropump with an integrated sensor based on space-division multiplexing

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ABSTRACT

This paper presents a new concept of a self-sensing piezoelectric micropump based on space-division multiplexing (SDM). By means of dividing the electrode of the piezoelectric diaphragm into two parts of driving unit and sensing unit, a sensor is integrated onto the piezoelectric micropump. A prototype micropump is fabricated from a finished segmented-electrode piezoelectric diaphragm in our laboratory. Through basic experiments using tap water as a working fluid, frequency and voltage characteristics of the flowrate, backpressure and sensing voltage are investigated. The frequency ranging 0–50 Hz can be determined by the sensing voltage. When the maximal flowrate of 26.55 ml/min is recorded at a driving frequency of 30 Hz, the sensing voltage also achieves the maximum of 3.02 V_{p-p} at a fixed excitation voltage of 150 V_{p-p}. Experimental results indicate there is pretty good agreement between the sensing voltage and the flowrate as a function of excitation frequency or voltage. Moreover, it indicates that the piezoelectric micropump itself can accurately determine the optimal frequency through monitoring the sensing voltage with the method of SDM. In the backpressure-voltage experiment, along with the backpressure changing from 0 to the maximum of 7.1 kPa at an excitation voltage of 210 V_{p-p}, the sensing voltage also changes from 0 to the maximal voltage of 16.6 V_{p-p} correspondingly at a fixed frequency of 30 Hz. Experimental result also shows there is a linear relationship between the backpressure and the sensing voltage. Therefore, both theoretical analysis and experiments prove that the self-sensing method based on SDM could well reflect the variation law of the flowrate and backpressure for piezoelectric micropumps. The micropump design shows the feasibility of our current effort to realize the measurement of the output flow and backpressure without the additional testing instruments.

1. Introduction

Microfluidic components are believed to have the potential for wide application in many fields, for example, chemical analysis, biological substances analysis, fuel cells, medical treatment [1,2]. Fluidic driving device is a key component for the transportation and distribution of minute and accurate amount liquid in a microfluidic system [3,4]. Hence, various micropumps have been developed for microfluidic transportation by using several actuation methods, such as piezoelectric, electromagnetic, pneumatic, electrostatic, electro-osmotic, or magneto-hydrodynamic effects [5–8]. Most of them have complex structures and high power consumption. On the contrary, piezoelectric actuation has advantages of a relatively simple structure, good reliability and lower power consumption [9–11]. Applications range from intravenous introduction of pharmaceutical drugs to bionic underwater propulsion [12–14]. The research on piezoelectric micropumps started from 1970s and various designs have been presented since then [15]. In theory, the output fluid flow per working cycle of piezoelectric micropumps is the volume change amount of pump chamber. So they can realize the precise control of the flow and pressure. However, there is a big impact of working conditions on the output flow and pressure in practice. Besides excitation voltage, fluid viscosity, temperature and loads directly influence the deformation of piezoelectric vibrators to result in the inaccuracy of the output flow. Therefore, the higher accuracy cannot still be gotten only through adjusting the excitation voltage and frequency. The additional measuring instruments of flow and pressure are still required to perform the real-time monitoring in some fields of precise microfluid transportation and control, like preparation of DNA, electrophoresis detection, PCR reaction, chemical analysis [16,17]. Not only the cost but also the volume, quality and

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complexity of the system are increased. It brings a serious hindrance to the promotion and application of the piezoelectric micropumps in micro-electro-mechanical systems and portable products.

Therefore, a few efforts have been made to integrate sensors onto the micropumps to improve their performance. Nguyen et al. presented the design, fabrication, and characterization of a micromachined flow sensor which is integrated onto the flexural plate wave micropump. The flow sensor and the micropump represented a complex microfluidic system that was able to control the fluid flow in the device [18]. To obtain high precision and to monitor the whole pipetting process, Szita et al. realized an all-in-one device for high-precision aspiration and dispensing through integrating two capacitive sensors into the piezoelectric micropipettor [19].

In this mode of segmented electrode, as one of the decoupling methods of realizing self-sensing actuators proposed by Dosch et al. [20], there are many successful implementations that direct and converse piezoelectric effect can be applied simultaneously in a piezoelectric transducer. A piezoelectric transformer (PT) is one of the classic applications. Up to now, various new kinds have been created and tested, like a dual-output plate type PT, a disk-shaped PT, a ring-shaped PT [21,22]. Arai et al. proposed a novel touch sensor with two electrodes on the PZT thin film. Using this sensor, they developed a novel screening system for separation of target microorganisms from the randomly distributed samples on the plate [23]. By patterning the electrodes of a piezoelectric layer, Campolo et al. made the sensing section and the actuating section coexist on the same piezoelectric layer [24].

In this paper, it is drawn lessons from space-division multiplexing (SDM) methods to construct the self-sensing piezoelectric micropump. As a term in communication engineering, SDM means that the different users can be distinguished according to their spatial position, that is, users in different locations may share the physical resources without interference. The piezoelectric diaphragm of the micropump is divided into two parts of driving unit and sensing unit through segmenting its electrode in this work. The driving unit is used to actuate the micropump. The sensing unit is used to monitor the deformation of the piezoelectric diaphragm. The deformation represents the volume change of pump chamber, namely the output flow of the piezoelectric micropump. Then the micropump realizes the fluid transportation and the output flow or backpressure self-testing simultaneously. Compared with the integration methods mentioned above, both direct and converse piezoelectric effect are concurrently used. Only adopting one SDM diaphragm, both sensing and driving function are realized. The principle of a SDM self-sensing piezoelectric micropump is analyzed. Through adopting a finished segmented-electrode piezoelectric diaphragm made in Murata company, a piezoelectric micropump with an integrated sensor based on SDM is fabricated. Then the implementation feasibility of the self-sensing piezoelectric micropump by this means is validated experimentally.

2. The principle and design of a SDM self-sensing piezoelectric micropump

The piezoelectric micropump uses a PZT actuator to move a diaphragm in a chamber providing fluid entrance and exit with the flow direction being controlled by check valves. A classic piezoelectric diaphragm micropump (Fig. 1(a)) consists of an inlet, one piezoelectric diaphragm, two check valves, one pump chamber, pump body and an outlet. When the piezoelectric diaphragm is operating in bending vibration mode, the pressured liquid in chamber propels the valves to open or close according to a certain regular. As a result of this, the liquid moves from the inlet to outlet continuously. As mentioned above, piezoelectric diaphragm micropump may realize the precise control of the flow and pressure theoretically. But some internal and external factors of the micropump actually bring a certain influence on its accuracy and controllability.

Therefore, the idea of space-division multiplexing in communication engineering is used for reference for this paper. With the method of segmenting electrode, a piezoelectric micropump with the sensing function could be obtained. The surface electrode of the original piezoelectric diaphragm of the micropump in Fig. 1(a) is divided into two parts, the larger area acting as driving unit and the smaller area acting as sensing unit, as shown in Fig. 1(b). When the AC power supply is applied on the driving unit, the voltage ranging from $-V_d$ to $+V_d$, it will make the piezoelectric diaphragm move downward to decrease chamber volume and increase the pressure, the outflow will be in one direction with inlet valve closed and outlet valve open. Meanwhile, the sensing unit also moves downward along with the piezoelectric diaphragm and its output voltage increase with the deflection, the voltage ranging from $-V_s$ to $+V_s$. When the excitation voltage ranges from $+V_d$ to $-V_d$, the driving unit makes the diaphragm move upward to increase the chamber volume, the inflow will enter into the chamber with the inlet valve open and the outlet valve closed. Similarly, the sensing unit also moves upward along with the piezoelectric diaphragm. Its output voltage will decrease from $+V_s$ to $-V_s$. It is seen from the overall working period of the micropump that in this way the sensing unit is subjected to the same deflection as the piezoelectric diaphragm. So the output voltage of sensing unit can represent the diaphragm's deflection information as well as the volume change of the micropump chamber.

When the excitation frequency is well below the resonant frequency of the piezoelectric diaphragm, its central displacement δ can be considered as constant and calculated by [15]

$$\delta = \frac{3}{4}\frac{g_{31}}{\pi t}C_e V_d \quad (1)$$

$$C_e = \frac{\varepsilon_{33}^T A_d}{t} \quad (2)$$

where V_d is the excitation voltage; t is the thickness of the piezoelectric element; A_d and C_e are respectively the area and the capacitance of the driving unit; g_{31} and ε_{33}^T are respectively the appropriate piezoelectric and dielectric coefficients. After substituting Eq. (2) into (1), Eq. (3) will be obtained.

$$\delta = \frac{3}{4\pi}\frac{g_{31}\varepsilon_{33}^T A_d V_d}{t^2} \quad (3)$$

Because of the relation between the piezoelectric and dielectric coefficients can be expressed as follows:

$$d_{31} = g_{31}\varepsilon_{33}^T \quad (4)$$

Eq. (3) may be converted as follows:

$$\delta = \frac{3}{4\pi}d_{31}\frac{A_d}{t^2}V_d \quad (5)$$

Because the sensing unit is subjected to the same deflection as the piezoelectric diaphragm, the sensing voltage V_s caused by the displacement δ at a certain excitation frequency can be given according to h-type piezoelectric equation of expressing the relation between electric field and strain.

$$V_s = h_{31}\delta = \frac{3}{4\pi}d_{31}h_{31}\frac{A_d}{t^2}V_d \quad (6)$$

The piezoelectric diaphragm is usually assumed to have a spherical displacement when a voltage is applied to it. The displaced chamber volume per stroke can be calculated by

$$\Delta V = \frac{\pi d^2}{8}\delta = \frac{3}{32}d_{31}\frac{A_d d^2}{t^2}V_d \quad (7)$$