Mechanical Systems and Signal Processing 41 (2013) 639–648

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Flow rate self-sensing of a pump with double piezoelectric actuators

Zhonghua Zhang, Junwu Kan *, Shuyun Wang, Hongyun Wang, Jianming Wen, Zehui Ma

Institute of Precision Machinery, Zhejiang Normal University, Jinhua 321004, PR China

ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
13 July 2013
Accepted 13 August 2013
Available online 6 September 2013

Keywords:
Piezoelectric pump
Self-sensing
Flow rate
Double actuators
Segmented electrode

ABSTRACT

According to the method of segmenting electrode, the flow rate self-sensing of a conventional piezoelectric pump with the actuators of double diaphragms is presented in this paper. The novel pump is characterized by the simultaneous function of fluid transportation and the flow rate self-testing through only one piezoelectric element. The analysis indicates that direct and converse piezoelectric effect can be concurrently applied to obtain the simultaneous function through dividing the electrode of the piezoelectric element into driving unit and sensing unit. With two commercialized segmented-electrode piezoelectric diaphragms, a prototype pump is fabricated with the size of 65 mm × 40 mm × 12 mm and tested according to the frequency characteristics at a fixed driving voltage and the driving voltage characteristics at a fixed frequency. The results show that sensing voltages of diaphragms are increased or decreased with the change of the flow rate as a function of frequency. When the flow rate reaches the maximum value of 45.98 ml/min at 15 Hz, outlet/inlet sensing voltages also reach maximum values of 6.80 V_{pp} and 19.4 V_{pp}, respectively. It demonstrates that the pump itself could accurately reflect the optimal frequency through monitoring outlet/inlet sensing voltages. The testing results indicate the good linear relationship between outlet/inlet sensing voltages and the flow rate as a function of driving voltage. Therefore, both theoretical analysis and experiments have proved that flow rate self-sensing can be realized for the piezoelectric pumps with double actuators through segmenting their electrode. Moreover, if any electrode of double piezoelectric actuators is segmented, the pump can obtain the complete self-sensing function.

1. Introduction

Small-scale flow pumps have been widely concerned because of their application potential in drugs delivery, chemical analysis, micro cooling system, propelling micro-spacecraft, etc. [1–3]. As a microsystem, the way to produce effective mechanical driving effect and precision flow control at microscale is the key investigated issue [4,5]. Piezoelectric mechanism is the most widely used in pumps and a piezoelectric pump is also an attractive topic because it has the

* Corresponding author. Tel.: +86 579 8228 8627; fax: +86 579 8228 8020.
E-mail addresses: zhangzhh@zjnu.cn (Z. Zhang), kanjw@zjnu.cn, jutkjw@foxmail.com (J. Kan), wshy888@yahoo.com.cn (S. Wang), emmawhy@zjnu.cn (H. Wang), wjming@zjnu.cn (J. Wen), zhma2010@126.com (Z. Ma).

0888-3270/$ - see front matter
http://dx.doi.org/10.1016/j.ymssp.2013.08.012

advantages of good reliability, energy efficiency, moderated displacement and fast response time [6–9]. Moreover, the displacement to pump the fluid can be easily controlled by an applied voltage through the simple fabrication process.

Piezoelectric pump utilizes the reciprocating motion of a diaphragm activated by a piezoelectric actuator and convert this motion into a pumping action. The research on piezoelectric pumps started from 1970s and various designs were presented [10]. Because the comparatively high actuation voltage is usually regarded as the disadvantage [11], a lot of efforts have been made in the research of pumps in order to achieve higher performance at lower actuation voltage. Further output performance improvement through optimization design is limited. As a result, piezoelectric pumps with double or even multiple actuators and chambers were successfully developed [12–16]. In 1998, Ullmann analyzed the performances of one single-chamber and one double-chamber piezoelectric valveless pump, respectively. It showed that the double-chamber pump yielded a significant improvement over its single chamber counterpart [14]. In 2008, in order to achieve high output performance at low actuation voltage, Kan et al. proposed serial multi-chamber piezoelectric pumps with cantilever valves and verified that the flow rate of the serial-connection multi-chamber pumps was increased with the increasing number of pump chambers through experimental results [15]. In 2010, Azarbadegan et al. analyzed the characteristics of double-chamber parallel valveless pumps and discussed the implications of these results for optimal pump design [16].

At the same time, there is a growing interest in the research on the integration of pumps and flow sensors, which are the two critical components of micro-liquid handling systems. A main reason is that actuating procedure of piezoelectric pumps is closely related to its microstructure, solid–liquid coupling and individual elements inside the system [17,18]. Furthermore, the integration of the components also brings other advantages to the liquid handling systems, such as the reduction in complexity degree, cost and size. In 2000, Nguyen et al. presented the design, fabrication, and characterization of a micromachined flow sensor which was integrated onto the flexural plate wave pump. The flow sensor and the pump represented a complex microfluidic system that was able to control the fluid flow in the device [19]. In 2001, to obtain high precision and monitor the whole pipetting process, Szita et al. presented an all-in-one device for high-precision aspiration and dispensing through integrating two capacitive sensors realized in silicon bulk micromachining onto the piezoelectric micropipettor [20]. In 2010, Zhang et al. presented a self-bended microcantilever flow sensor that consisted of two silicon dioxide layers and a single crystalline silicon piezoresistor in-between. This configuration had the advantage of high sensitivity for low flow rate measurement and allowed the microcantilever to be integrated in microchannels to measure steady flow [21]. In 2012, Fuchs et al. presented the integration of a piezoelectric peristaltic pump and a sensor which was based on a piezoresistive strain gage technology and directly integrated on the silicon membranes [22]. These work showed that the built-in sensors would provided an important benefit as they enabled a better control over the pumps. Moreover, they could generate a lot of useful information which could not be given by standard external sensors. The above researches show that some efforts have been made to integrate sensors onto the pumps to improve their performance. However, in most of the works on the integration of pumps and flow rate sensors, the silicon MEMS technology is adopted for the fabrication. The integration of the sensors and the piezoelectric pumps fabricated with conventional production techniques and materials was rarely reported.

In this paper, pursuing the above two research focuses on the pumps, we aim to present the integration of the sensors and the conventional piezoelectric pumps with double actuators. With the method of segmenting electrode, the novel pump could theoretically perform fluid transportation using converse piezoelectric effect and flow rate self-testing using direct piezoelectric effect simultaneously. Compared with the integration methods mentioned above, the proposed method concurrently realized both sensing and driving function through only one piezoelectric element. A double-actuator and single-chamber piezoelectric pump with an integrated sensor is analyzed and fabricated. The operating frequency and driving voltage characteristics of the prototype pump are experimentally investigated. It shows the possibility of the flow rate closed-loop control or on-line monitoring without an external sensor for the piezoelectric pumps using traditional techniques.

2. Principle and design

Because of its simple planar structure, the piezoelectric thin diaphragms are appropriate to structure the pumps with double even multiple actuators and chambers to enhance output capability. With double actuators, the serial or parallel piezoelectric pumps could be configured. According to their different connection modes with AC power supply, the double actuators can work synchronously or asynchronously. For example, the phase difference of driving voltages of the double actuators is 0° or 180°. Meanwhile, owing to different installation modes and amounts of check valves, the pumps with double actuators is in the single-chamber or double-chamber structure form. A classic double-actuator and single-chamber piezoelectric pump consists of an inlet, two piezoelectric diaphragms used as actuators, two check valves, one pump chamber, pump body and an outlet, as shown in Fig. 1(a). When the double actuators are operating in the synchronous mode, the piezoelectric diaphragms will be simultaneously bent outward or inward. It makes the pump chamber expand or compress and the chamber pressure is increased or decreased. The pressured liquid in chamber propels the valves to open or close according to a certain regular. As a result, the liquid moves from the inlet to outlet continuously. In order to achieve the integration of the flow rate sensor and the double-actuator and single-chamber pump, the method of segmenting electrode is adopted to realize a piezoelectric pump with the sensing function in this paper. Actually, in this mode of segmenting electrode, the direct and converse piezoelectric effect can be applied simultaneously on a piezoelectric