Sensors and Actuators A 244 (2016) 126–132

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Elastic string check valves can efficiently heighten the piezoelectric pump's working frequency

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ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 23 March 2016
Accepted 9 April 2016
Available online 11 April 2016

Keywords:
Piezoelectric micropump
Power density
String check valve

ABSTRACT

This study presents the design, analysis, fabrication process and experimental results of elastic string check valves for high frequency and high flow rate piezoelectric pumps. The moving part of the check valve is elastic rubber strings. Analysis revealed that the rubber string valve could exhibit high working frequency and is beneficial to construct large outflow pumps. A separable micropump was designed for testing frequency performance of the string valve. Experimental results demonstrated that the flow rate almost increased linearly with driving frequency below 1 kHz despite the first resonant frequency of the rubber string occurring at only 488 Hz. The maximum flow rate of water was 67.1 mL/min when the micropump was driven with a sinusoidal voltage of 170 V_{pp} at 1 kHz.

1. Introduction

Research and development of various types of piezoelectric micropumps have been continuously conducted since 1978 when one of the earliest piezoelectric micropump for insulin delivery was fabricated [1]. Given the simple structure, good reliability, no magnetic influence, small volume and low power consumption, piezoelectric micropumps have received considerable attention in chemical [2], biomedical [3], space and military [4,5] applications with significant scientific and commercial potential.

The maximum power density of piezoelectric material is directly proportional to its working frequency [6]. Therefore, the operating frequency of a micropump should be increased to obtain high power density of piezoelectric material and high flow rate of the pump. However, commercially available check valves usually work below 500 Hz. Low frequency response of check valves has hindered the increase of operating frequency of micropumps. Valveless pumps have no check valves and present better high-frequency characteristics [7], but it is hard to control flow in only one desired direction through outlet or inlet channels, which causes serious energy loss and liquid reflux. Thus, they are not suitable for applications that require high flow rate and precise control of flow rate. By contrast, micropumps with check valves show better performance in managing both flow direction (forward or backward) and resolution. Therefore, a high-frequency check valve is imperative for high-performance micropumps.

Current research on check valves can be classified into active and passive valves [8]. In 2007, Cheng et al. [9] devised a piezoelectric pump with the inlet and outlet valves controlled by magnetic coils. Most active microvalves couple a flexible membrane to magnetic [10], electric [11], piezoelectric [12], thermal [13], or other actuating elements. Additional power consumption is required for active valves because active valves need additional control unit to operate. Passive valves operated by pressure difference are incorporated in inlets and outlets of reciprocal displacement micropumps as mechanical moving parts, such as spherical balls [14], cantilever-type [15], and bridge-type [16]. Nevertheless, traditional passive valves often present low frequency responses. When the physical dimensions shrink, micromechanical passive valves can achieve higher operational frequency. The diaphragm thickness of high-frequency microvalve using micro electro mechanical systems (MEMS) technology can reach below 20 μm [17]. Li et al. [18] fabricated a cross pattern bridge-type microvalve with electroformed nickel on silicon substrate. The whole valve weighs 0.2 g and can work at frequency higher than 10 kHz. Lee et al. [19] presented a microvalve array with high operational frequency of 50 kHz. However, these valves perform well only at high pressure difference, thereby resulting in large energy waste and low efficiency. Besides, their fabrication processes are relatively complex and expensive with high precision processing required. Surface treatment and

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http://dx.doi.org/10.1016/j.sna.2016.04.026
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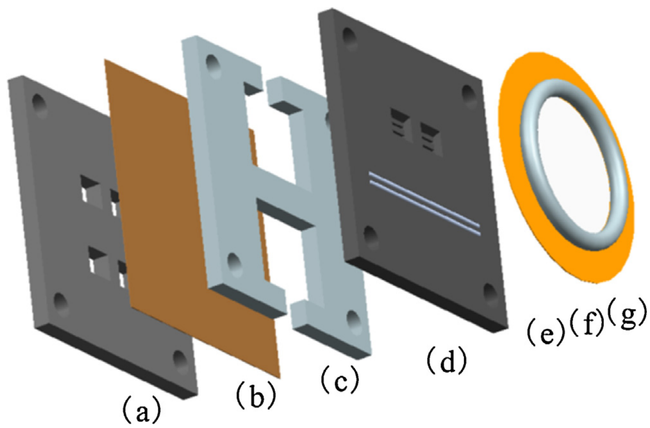

Fig. 1. Exploded view of the designed piezoelectric micropump: (a) PMMA plate with holes, (b) PDMS thin film, (c) PMMA plate with flow channel, (d) seat plate with inlet and outlet valves, (e) bottom o-ring, (f) piezoelectric disc, and (g) top o-ring.

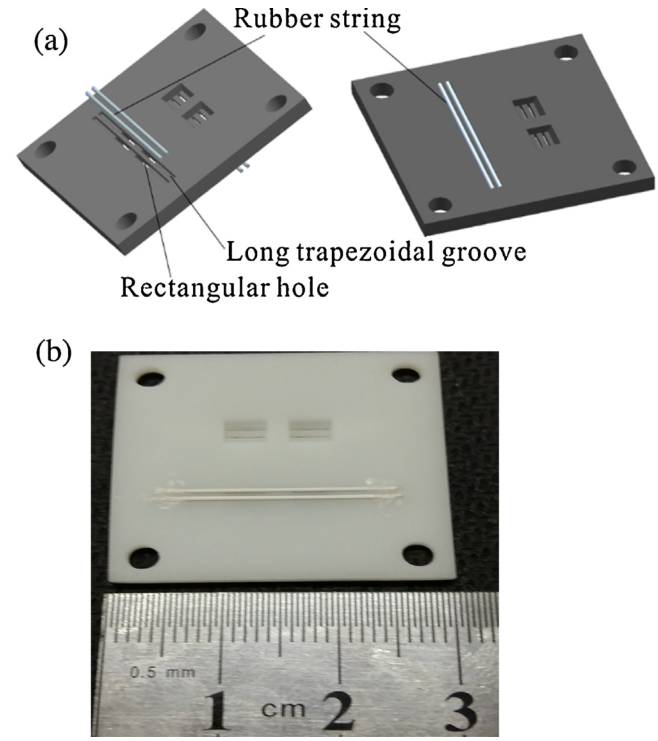

Fig. 2. Detailed description of the check valve. (a) Structure of the check valve, (b) photograph of the check valve.

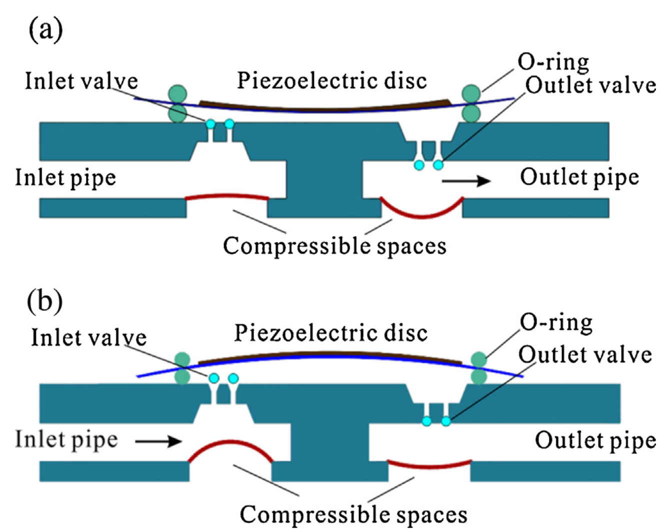

Fig. 3. Operation principle of the proposed micropump. (a) Dispensing mode and (b) absorbing mode.

cleaning of microvalves significantly affect the normal working performance.

A string-type passive check valve for high frequency and high flow rate pumps is proposed in this paper. The main component of the valve is elastic rubber strings. The working frequency of the string-type valves is up to 1 kHz, and the design does not require complex microfabrication. A piezoelectric micropump is also designed to evaluate the string-type valves' performance. This novel string-type valve can be potentially applied to high powered hydraulic devices for space and military applications [19–21].

2. Design of the pump

2.1. Pump structure and string valves

Fig. 1 shows an exploded view of the designed piezoelectric micropump with the string-type passive check valves in this study. The separable micropump is divided into top structure and substructure. The top structure includes a piezoelectric disc (f), which serves as an actuator, and two o-rings (e, g), which are used to support the actuator and construct pump chamber. Two o-rings are placed on 'zero' deformation location (detailed in Section 2.3) of the piezoelectric disc, so they barely restrain the vibration of the piezoelectric disc under ideal conditions. Instead of using the entire working area of the actuator as usual, this top structure only uses inner part of the actuator to push or pull the liquid in the pump chamber. The o-ring (e) on the bottom serves as a part of the pump chamber and accommodates the working fluid. After assembly of the top structure, it is directly placed on a seat plate with inlet and outlet valves (d), and then fastened by two stainless steel cover plates (detailed in Section 3.1). The substructure consists of a seat plate with valves, a flow channel plate, and a mechanism for compressible spaces. The compressible spaces are constructed by a polymethyl-methacrylate (PMMA) plate with flow channels (c), a piece of polydimethylsiloxane (PDMS) thin film (b), and a PMMA plate with holes (a). It has been proved that compressible spaces can smoothen the flow rate pulsation of the liquid in the inlet and outlet pipes, and improve a piezoelectric pump's performance [22]. The dimensions of the piezoelectric disc and PMMA plate are ϕ26.9 mm × 0.34 mm and 30 mm × 30 mm × 2 mm, respectively. The thickness of PDMS film is 0.1 mm.

The string-type check valve consists of a valve seat and flexible rubber strings. There are long grooves and rectangular holes on the seat plate. Two ends of the rubber string are glued in long trapezoidal grooves and the string covers the rectangular holes at equilibrium position. The valve is open when the string is forced to bend away from the rectangular holes, and the valve is closed when the string is forced to cover the rectangular holes tightly. Fig. 2 presents the specific structure of check valve. The thickness of the valve seat is 2 mm. The sizes of rubber string and rectangular hole are 0.5 mm (D) × 22 mm (L) and 0.3 mm (W) × 4 mm (L), respectively.

Fig. 3 presents the operation principle of the micropump. As shown in Fig. 3(a), when the piezoelectric disc's center part bends downward to decrease the pump chamber's volume, the inlet valve closes and the outlet valve opens with the increased chamber pressure. As shown in Fig. 3(b), when the actuator bends upward to increase chamber volume, the outlet valve closes and the inlet valve opens with decreased chamber pressure. With the actuator excited