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Development of large flow rate, robust, passive micro check valves for compact piezoelectrically actuated pumps

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Abstract

A robust passive high frequency high pressure micro check valve was developed for piezoelectrically actuated pumps. A novel cross-patterned microvalve flap is used to increase the valve's structural stiffness with pressures up to 10 MPa. A mechanical valve stopper prevents valve-flap failure under extreme high pressure. The valve-flap is also designed to work at frequency larger than 10,000 Hz. The valve-flap was fabricated with electroformed nickel on silicon substrate. Deep RIE etching was used to fabricate the valve channels in the silicon substrate. The whole valve weighs 0.2 g including packaging. The microvalve flow rate (water) is measured to be 18 cm^3/s under a pressure difference of 50 psi. The microvalve was integrated with a compact piezoelectric pump and produced pressure of 350 psi when operated at 10 kHz frequency.

Keywords: Microvalve and array; Hydraulic actuator; Electroforming; Large flow rate; High frequency; High pressure

1. Introduction

Compact actuators are currently being proposed for space related structural applications [1,2]. Compact robust actuators are important because they provide larger power per unit volume/weight ratio than conventional actuators. Actuator requirements include large displacement, large output force, high bandwidth, and high precision together with a compact size. One example is that NASA intends to reduce the launching cost dramatically from current US$ 8000/pound to 100/pound by 2025 [4]. Miniaturization will play an important role for achieving the objective, as any reduction in mass or power required for a space instrument or subsystem results in an exponential savings for launch cost [2]. MEMS based microvalves and compact piezoelectric pumps represent key components for fluid management systems to meet the rigorous performance requirements for a variety of space applications. For example, NASA has identified a low-leak space qualified regulator valve as a key technology for enabling micro-instruments, micro-spacecraft, and the future of space exploration [2].

Hydraulic compact actuators consisting of piezoelectric stacks and robust microvalves represent an alternative to other compact actuators. These hydraulic actuators produce power per unit volume ratio about 100–1000 times greater than electrostatic counterparts [5,6]. Compact pumping components (pusher) are fabricated with smart (active) material due to simplicities in design and high power densities. These smart materials include, but are not limited to, piezoelectric materials, magnetostrictive materials, shape memory alloys and phase change materials [7]. Requirements for compact pumping components include large displacement, large force output, high working frequency, low energy consumption (high efficiency) and easy operation. Generally speaking, piezoelectric materials produce larger force outputs at high

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operation frequency (up to 100 kHz) with small displacements (<0.5%); shape memory alloys produce large displacement (up to 8%) and very high energy density with low working frequencies (<100 Hz). Other materials and/or driving mechanisms are ranked in between the piezoelectric material and shape memory alloys, in terms of force, displacement output and the operational frequency.

Robust microvalves are required to perform two functions in a hydraulic actuator (pump). One function is manipulating/directing/switching the flow direction (forward or backward) and another function is to bear the load when the valve is in a closed state. Therefore, requirements for compact valves are stricter than for a pumping component (pusher), in addition to those common limitations encountered in MEMS devices [2]. Nevertheless, valves should be able to open wide (enhancing forward flow) and close tightly (preventing back flow). High frequency is required for microvalves to produce high flow rates thus large displacements could be achieved for the hydraulic actuator.

Current research on microvalves can be classified as active (self controlled) valves and passive (controlled by the pressure difference produced by the pusher) valves [7–19]. Research on non-mechanical moving parts or valveless system is not referenced in this article due to the small pressure gradient and/or small flow rate produced. In general, active valves have a relatively quicker response time or higher frequency response (for example, up to 100 kHz for piezoelectric valves). However, they provide low to moderate flow rates due to either small displacement (piezoelectric) or longer response time (shape memory alloys). The active valves also need additional control unit (power activated) to operate the valve and additional power consumption is required. In addition, the synchronization between pumping component (pusher) and the valve is challenging at high frequencies.

On the other hand, passive valves or check valves are opened by pressure differences created by the pumping component (pusher). These valves have been successfully tested in both macro scale and micro scale applications [7–9]. While successful, these passive valves are typically more susceptible to back flow problems and traditional passive valves are considered to be low frequency, i.e. <500 Hz [7]. Scaling laws have proven that micro mechanical systems could be changed greatly when the physical dimensions shrink [9] and they should apply equally to robust microvalves.

This paper investigates the feasibility of utilizing micro mechanical passive valves to achieve high operational frequency, large flow rate and large pressure for a robust compact piezoelectrically actuated pump. A novel micro reinforced valve-flap is used to provide high-pressure capabilities, i.e., 10 MPa when the valve is closed. The valve-flap is also designed to work at frequency larger than 10,000 Hz and to prevent potential tear-off of the valve-flap under extreme high pressure when it is open. Test results show that 18 cm^3/s flow rate can be achieved under a pressure of 50 psi. The work indicates that microvalves can be used to support macro forces (>10 MPa) and large flow rate (>10 cm^3/s) with fast operation frequency (>10 kHz).

2. Microvalve design

The micro mechanical passive valve designs are based on requirements for compact hydraulic actuators being developed for space applications [1,3]. The requirements on the integrated microvalves include: (1) ability to support pressures of 10 MPa or larger; (2) flow rate of 10 cm^3/s or larger; (3) operating frequency of 10 kHz or larger; and (4) low or no power consumption. Current MEMS based valves can meet all these requirements.

Fig. 1 is a sketch of the microvalve design integrated with a compact robust pump (the hydraulic actuator) being developed. A piezoelectric stack is used as the pump pusher which produces large pressure and high flow rate when operated at high operating frequency. The pump pusher (PZT) deforms a membrane to compress the liquid in the chamber to open the valve. The pump is 50 mm long and 25 mm in diameter (Fig. 1).

The microvalve developed is a micromechanical normally-closed check valve (Fig. 2 and Fig. 1B for array). The microvalve consists of one inlet/outlet channels and a novel nickel valve-flap, as well as a valve stopper (Fig. 2). Liquid is directed through orifice of the valve-flap and passing the outlet channels fabricated on the valve stopper. The gap between valve-flap and valve stopper is 10 μm. The valve-flap (Fig. 2) is linked with four long (400 μm) identical micro beams (springs), which hold the valve-flap attached to the valve substrate and thus closes the valve channel (200 μm in diameter, Fig. 2) elastically. The valve is opened by a pressure pulse produced by the PZT actuator (Fig. 1A) forcing liquid pass the valve channel through the valve-flap (Fig. 2). The valve returns closed by the spring force developed in the four beams in addition to the reverse pressure difference upon PZT's contraction (Fig. 1). The size of the valve-flap (square) is 300 μm × 300 μm held by four beams (50 μm × 400 μm each) and the thickness is 10 μm for both the valve-flap and the beams.

A cross pattern nickel structure (300 μm × 40 μm × 20 μm) is designed on top of the valve-flap (Fig. 2). The

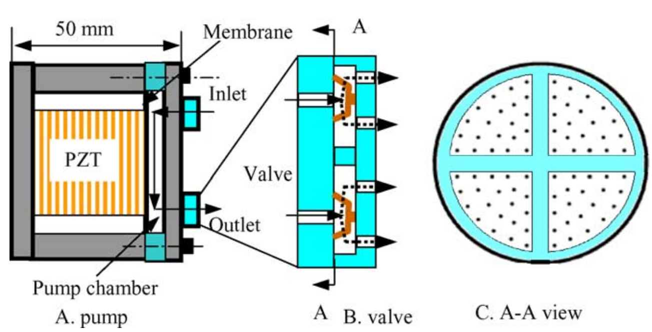

Fig. 1. Sketch of compact pump and integrated microvalves (not in scale).