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A piezoelectric microvalve with a flexure-hinged driving frame and microfabricated silicon sealing pair

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ABSTRACT

This paper describes a piezoelectric microvalve for attitude control of micro-satellite with a mass in the range of 20–100 kg. The microvalve comprises of a driving mechanism with a flexure-hinged frame and a valve body with a silicon sealing pair. The silicon valve core with sealing rings can achieve a low leak rate with a small structural deformation. The driving mechanism using a flexure-hinged frame and piezoelectric actuators assures the microvalve normally closed and leads to a fast response of the microvalve. The response time of the driving mechanism is characterized to be as small as 0.6 ms. A maximum flow rate of 3100 mL/min is achieved at an inlet pressure of 0.6 MPa while applied with a maximum voltage of 200 V. The static power consumption is 48 mW with a driving voltage of 200 V, and the dynamic power consumption is approximately 0.9 W at 100 Hz.

1. Introduction

Micro-satellites are drawing many attentions in the field of astronautics for their lightweights, low costs, short development cycle and high function density [1,2]. Constellations of micro-satellites with masses in the range of 20–100 kg arranged in the low earth orbit have significant applications in remote sensing and space experiments [3]. The micro-satellite requests the thrust within the range of 0.005–0.05 N and the impulse bit reach the order of 10^{-5} N s [4]. For propulsion system which uses fluidic propellant, the thrust and impulse bit are determined by the propellant flowing from the propellant tank which is controlled by a valve. Conventional electromagnetic valves used in existing large satellites suffer from high power consumption, which limits the application to the micro-satellites [5–8].

Many researches are focusing on the miniaturization of the valves. A miniature electromagnetic valve which is used to monopropellant hydrazine thruster is reported [9]. This valve can be operated at an inlet pressure up to 2 MPa with a leak rate as low as 10^{-4} mL/min. However, its power consumption is as high as 8 W. Other miniature electromagnetic valves are also not applicable to micro-satellites due to relatively high power consumptions [10,11]. Micromachined microvalves using electrostatic [12–14], thermal [15,16] and piezoelectric [17–19] transduction mechanisms have great reductions in their sizes, masses and power consumptions. However, most of these microvalves cannot meet the requirement for the low leak rate under a relatively high inlet pressure. One of the few microvalves meeting the requirement is a piezoelectric microvalve reported by Yang et al. [20]. It can be operated at a relatively high inlet pressure of 1.38 MPa with a low leak rate of 3×10^{-4} mL/min. However, the piezoelectric stack actuator suffers from tensile stress when the microvalve is in closed status, which will induce damage to the piezoelectric ceramics [21–23]. In addition, its seating pressure is not adjustable for its highly simplified mechanical driving mechanism. This paper describes a new leak-tight piezoelectric microvalve capable of operating at a relatively high inlet pressure with a flexure-hinged driving frame and a microfabricated silicon sealing pair, which achieves a low power consumption and good dynamic performance.

2. Design of the microvalve

As shown in Fig. 1, the microvalve comprises of a driving mechanism and a valve body. The driving mechanism includes a flexure-hinged frame, two piezoelectric actuators, a preloading screw, a sliding ball and two regulating screws. The valve body mainly includes a silicon valve core, a silicon valve seat, a lower body, and an upper body.

The microvalve is normally closed due to a preloading force applied to the silicon valve sealing pair. The preloading force originates from the upward bending deflection of the upper beam during the rotation of the preloading screw. It is then transferred in sequence from the preloading screw to the T-rod, the pin, and

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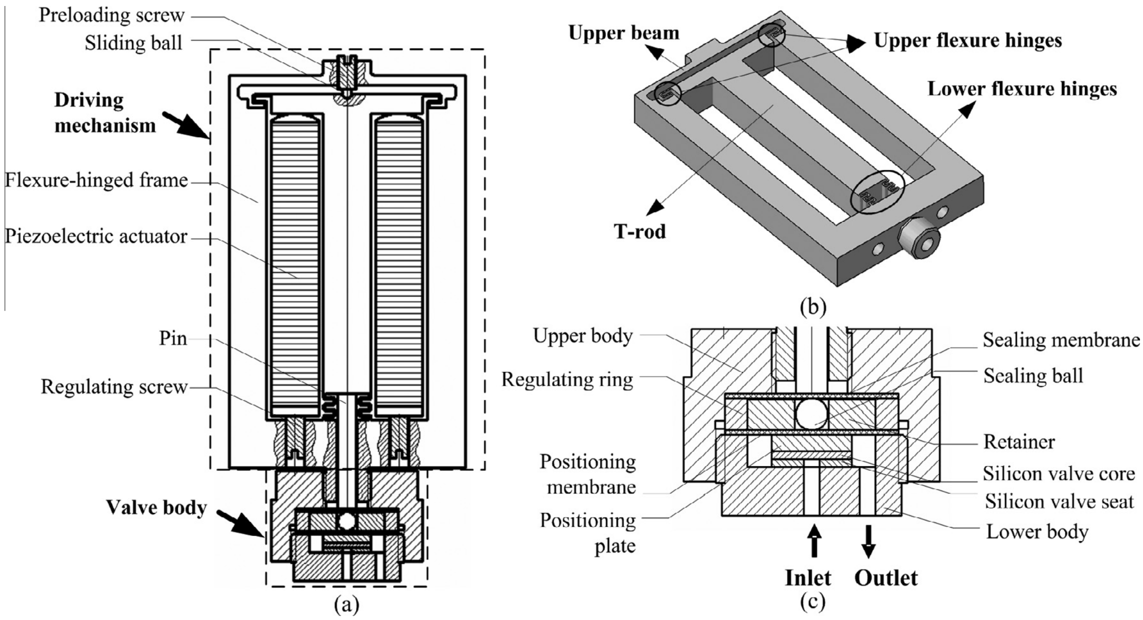

Fig. 1. Schematic structure of the microvalve. (a) The structure of the microvalve. (b) The diagram of the 3D geometry model of the frame. (c) The cross-sectional view of the valve body.

the silicon sealing pair. During the open status, the piezoelectric actuators are applied with a driving voltage and elongate to lift the T-rod. This removes the preloading force applied to the silicon valve core and seat. The silicon valve core is lifted due to the inlet pressure and the propellant flows from the channel between the valve core and seat. In addition, the flow rate is determined by the inlet pressure and the clearance between the valve core and seat.

2.1. Design of the flexure-hinged frame

As shown in Fig. 1, the flexure-hinged frame is the key component of the driving mechanism. It is fabricated by wire electro discharge machining (WEDM) from a plate of alloy steel (1Cr18Ni9Ti) whose modulus of elasticity is 206 GPa. As shown in Fig. 1b, the upper beam of the frame is used to produce preloading force by bending. The T-rod is used to transfer the elongating and shrinking deformation of the piezoelectric actuators to the rising and declining of the T-rod itself. The T-rod is connected to the frame by four flexure hinges. The flexure hinges are designed to have a low stiffness in the main deformation direction of the piezoelectric actuators, to reduce the resistance to the motion of the T-rod in the same direction. The key dimensions of the frame are illustrated in Fig. 2. The specifications of the two piezoelectric stack actuators are listed in Table 1. The pin is machined from bearing steel (GCr15) whose modulus of elasticity is 206 GPa. The radius of the cross section of the pin is 1 mm and the length of the pin is 12.7 mm.

The total stiffness of the four flexure hinges (k_{hi}), the stiffness of the upper beam (k_{up}) and the stiffness of the horizontal part of the T-rod (k_T) were calculated by the static analysis in the finite element software ANSYS. The corresponding deformations of the four flexure hinges, the upper beam and the horizontal part of the T-rod

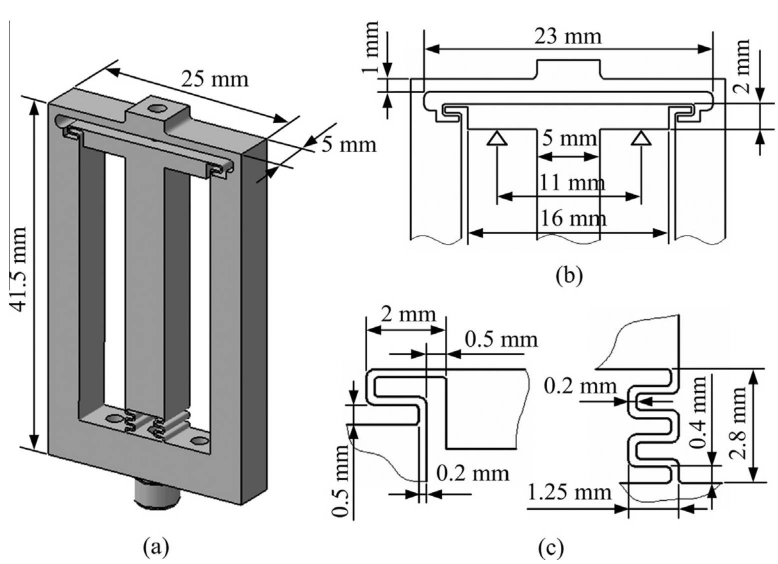

Fig. 2. Critical dimensions of the frame.