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Development of a piezoelectric pump using hinge-lever amplification mechanism

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Abstract This paper presents the design, fabrication, and tests of a piezoelectric pump using hinge-lever amplification mechanism. The proposed hinge-lever amplification mechanism consists of a base frame, a lever with contact steel ball, and a multilayer piezoelectric actuator. The lever is in contact with the piezoelectric actuator through hinged steel ball. The extended piezoelectric actuator pushes the contact steel ball; therefore, a small displacement of piezoelectric actuator can be amplified through the movement of the lever. The amplified displacement of 683 μm was measured at the applied voltage of 100 V. These results show the fact that the proposed hinge-lever mechanism can be obtained the amplification ratio of up to ten times. The piezoelectric pump using hinge-lever amplification mechanism was fabricated and pumping performance was experimentally investigated. The pump achieved no-load flow rate, maximum output pressure of 600 ml/min and 6.8 kPa, respectively, at the applied voltage of 100 V and driving frequency of 250 Hz.

Keywords Multilayer PZT · Displacement amplification · Hinge-lever mechanism · Piezo-electric pump

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1 Introduction

Recent development trends in electronic devices and microprocessor architecture have focused on the increasing integration density, miniaturizing processors, and increasing clock frequencies. As a result of these trends, heat generation rates of the electronic components have rapidly increased. Traditional electronics cooling solutions, such as a forced air convection cooling method using conventional fan assembled fin-array heat sinks and heat pipe technology, are unsuitable for counteracting these large heat generation rates [1, 2]. Among current state-of-the-art technologies, forced liquid cooling using a pump and heat sinks is an attractive solution for dissipating the heat flux from the high-power electronic devices. The pump plays a significant role in the forced liquid cooling system, which is required to drive the flow of working fluids through heat sinks.

On the other hand, the piezoelectric actuators provide a number of alternatives in the areas of precision machinery applications because of their precise, well-controllable displacements, and good force transmissions [3]. However, the major defect of conventional piezoelectric actuators is their small relative deformation, which is a few micrometer displacements within reasonable materials thickness and applied voltages [4]. By staking piezoelectric layers and metal electrodes, one can improve the displacement performance with the same electric field and without loosing force on the expense of extended device volume and materials costs [5, 6]. A hinge-lever mechanism which amplifies the small input displacement of piezoelectric actuators is one promising strategy to overcome the small displacement problem of

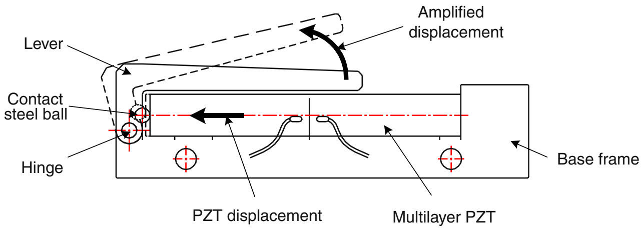


Fig. 1 Schematic diagram of the hinge-lever amplifier

Table 1 Specification of the multilayer PZT

Maker	NEC/TOKIN
Model No.	AE1010D44H40
Driving voltage [V]	100
Max. displacement [μm]	28
Blocking force [N]	3500

the piezoelectric actuators. Indeed, several precision machinery systems, such as piezo-driven micro positioning stages and micro actuators etc., have been built that utilize the hinge-lever amplification mechanism [3–8].

The objective of this study is to realize a pump, which could act as a fluid power source for a forced liquid cooling system. In this paper, mechanically amplified large displacement piezoelectric actuators using hinge-lever amplification mechanism is proposed, fabricated, and experimentally investigated in order to supply the driving source for the PZT pump.

2 Design of hinge-lever amplifier

The schematic diagram of the hinge-lever amplifier is shown in Fig. 1. The proposed hinge-lever amplification mechanism consists of a base frame, a lever with contact steel ball, and two multilayer piezoelectric actuators. Two multilayer piezoelectric actuators are bonded together using the epoxy. The lever is in contact with the piezoelectric actuator through the contact steel ball. When a direct connect voltage is applied to the two multilayer piezoelectric actuators, the extended piezoelectric actuator pushes the contact steel ball; therefore, a small displacement of piezoelectric actuator can be amplified through the movement of the lever.

Figure 2 shows the schematic diagram for the theoretical approach of the hinge-lever amplification mechanism. As can be seen in this figure, the theoretical amplified displacement S of the hinge-lever is derived as shown in Eq. 1.

$$S = L'y - Ly = L\left[\sin\left(b + a_p\right) - \sin b\right] \quad (1)$$

Where

the initial height of the hinge-lever $L_y = L\sin b$;
the height of the hinge-lever after moving $L_y' = L\sin(a_p + b)$;
the angular displacement of the lever $a_p = \cos^{-1}(l_x - s/l) - \cos^{-1}(l_x/l)$;
the initial contact point angle $b = \tan^{-1}(L_y/L_x)$.

The used multilayer piezoelectric actuator (AE1010D44H40, NEC/TOKIN Inc., Japan) can be generated the maximum displacement of 28 μm at the applied voltage of 100 V. The specifications of the multilayer piezoelectric actuator are listed in Table 1.

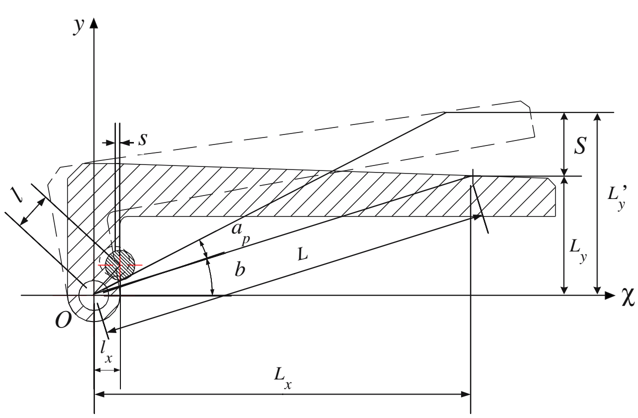


Fig. 2 Schematic diagram for the theoretical approach of the hinge-lever amplifier

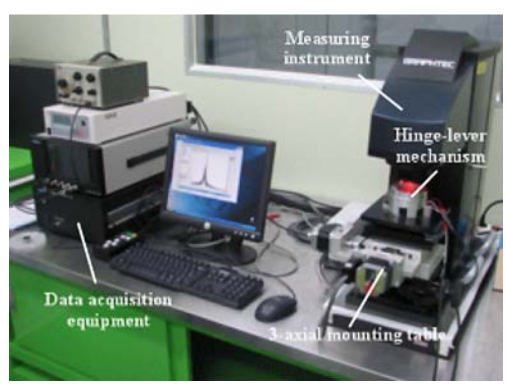
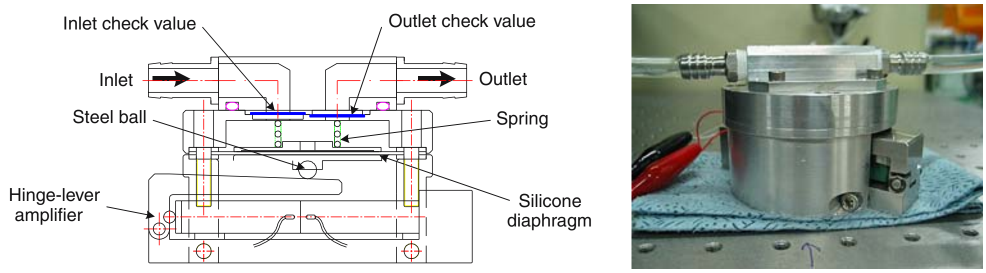


Fig. 3 Experimental apparatus for measurements of the amplified displacement of the hinge-lever amplifier



(a) schematic diagram **(b)** photograph

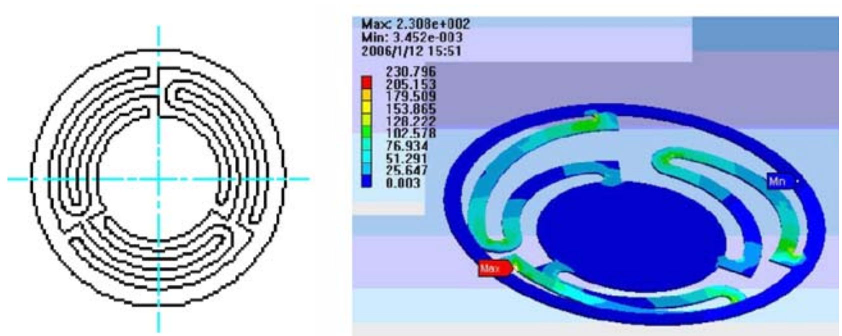
Fig. 4 Schematic diagram and photograph of the fabricated diaphragm PZT pump

Figure 3 shows the experimental apparatus for displacement measurements of the proposed hinge-lever amplification mechanism. In experiments, the laser-Doppler displacement meter (AT7500, Graphtec Co. Ltd., Japan) was used to measure the amplified displacement of the lever. The amplified displacement of 683 μm was measured at the applied voltage of 100 V. The fabricated hinge-lever amplifier had a distance l between the hinge and contact steel ball of 4.8 mm, a distance L_x between the hinge and contact point of 50 mm, and an initial height L_y of the hinge-lever of 15.9 mm. Using the Eq. 1, the calculated displacement of 696.6 μm was obtained and the measured error is about 2%. These results show the fact that the proposed hinge-lever mechanism can be obtained the amplification ratio of over ten times.

3 PZT pump using hinge-lever amplifier

The diaphragm PZT pump using hinge-lever amplification mechanism was designed and fabricated. Figure 4 shows the schematic diagram and photograph of the fabricated diaphragm PZT pump. The fabricated pump consists of the hinge-lever amplification mechanism, silicone diaphragm, inlet/outlet sheet type check valves, and spring. Overall dimensions of fabricated pump have a diameter of 80 mm and a height of 65 mm. Two sheet type check valves have an inner diameter of 9 mm and a thickness of 80 μm were used and the maximum yield stress of 230 MPa was estimated through the finite element method (FEM) analysis as shown in Fig. 5.

Figure 6 shows the schematic diagram of the experimental apparatus. It consists of the fabricated PZT pump, a piezo amplifier (HSA4052, NF Corp., Japan), a function generator and measurement instrumentations. Sinusoidal voltage of 100 V_{pp} was applied to the two multilayer piezoelectric actuators and driving frequency was changed. The measurement of flow rate during a 1-min was performed using a digital balance. The load pressure can be applied to the PZT pump by means of a rising height of drain port. The pumping experiments were performed using water for the working fluid.



(a) schematic diagram **(b)** FEM analysis result

Fig. 5 Schematic diagram and FEM analysis result of the sheet type check valve

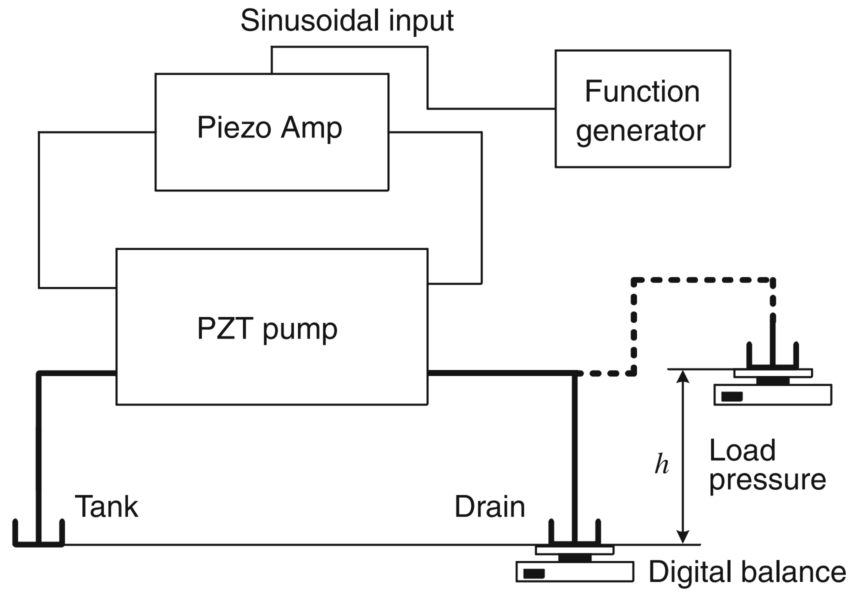


Fig. 6 Experimental apparatus for pumping characteristics of the PZT pump

The pumping experiments, such as no-load flow rate, maximum output pressure and load characteristic, were investigated as functions of the driving frequency. The measured results of the no-load flow rate and load characteristic for the fabricated PZT pump are shown in Fig. 7. As can be seen in this figure, the no-load flow rate of 600 ml/min and maximum output pressure of 6.8 kPa were achieved at an applied voltage of 100 V_{pp} and driving frequency of 250 Hz. Also, there is a nearly linear relationship between the flow rate and load pressure. Thus, a maximum output power of 17 mW is obtained at an applied voltage of 100 V_{pp} and driving frequency of 250 Hz.

4 Conclusions

A diaphragm piezoelectric pump using hinge-lever amplification mechanism was proposed, designed, and fabricated. The proposed hinge-lever mechanism can be obtained the amplification ratio of over ten times. The pumping characteristics of the fabricated PZT pump using the hinge-lever amplifier were experimentally investigated. The fabricated pump achieved the no-load flow rate and maximum output pressure of 600 ml/min and 6.8 kPa, respectively, at an applied voltage of 100 V_{pp} and driving frequency of 250 Hz.

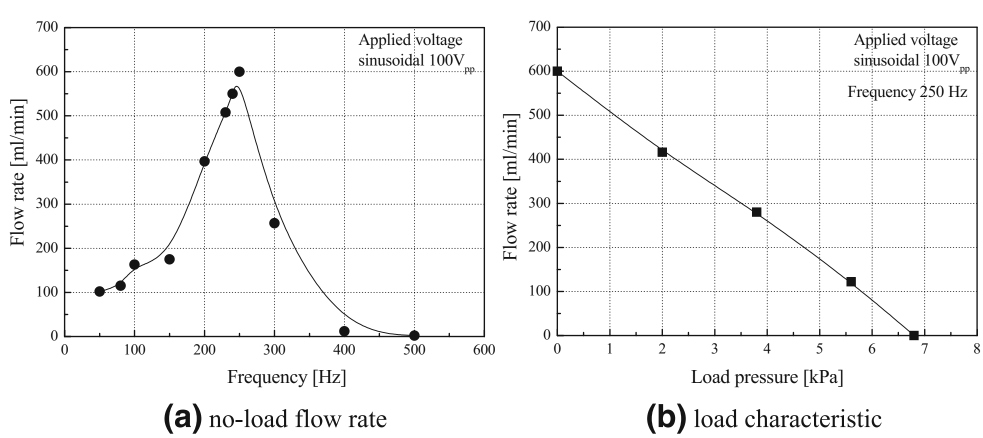


Fig. 7 Pumping characteristics of the PZT pump using hinge-lever amplification mechanism

Future work will focus on improvement of the pumping performance and miniaturization of the pump size.

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