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Development of a piezoelectric micropump with novel separable design for medical applications

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ABSTRACT

An innovative separable piezoelectric micropump has been developed to provide low-cost liquid delivery for medical applications. The actuator of the proposed micropump can be used repeatedly to reduce costs, and the pump chamber is disposable to prevent contamination as well as infection. The micropump was fabricated on a highly accurate CNC machine. A piezoelectric plate measuring 22 × 40 × 0.7 mm was used as the actuator and the operating voltage was AC 50–80 V. Moreover, a unique bossed diaphragm, with a cylindrical protrusion at its center, was designed to not only facilitate contact between the diaphragm and piezoelectric actuator but also to overcome the adhesive force, which is a major challenge facing separable micropumps. According to the results of experiments, the adhesive force caused by residual liquid in the pump chamber may adversely affect the resilience of the diaphragm, leading to an insufficient liquid supply. The results show that the thickness and bossed ratio of the diaphragm have a major effect on the flow profiles. To achieve the optimal performance, a 0.3-mm bossed diaphragm was combined with a pump chamber with a depth of 1 mm. The flow rate of the proposed optimal separable micropump can be modulated from 1.58 to 6.21 ml/min at frequencies of less than 20 Hz, and the pump head can reach a maximum of 200 mm-H_2O.

1. Introduction

The development of precision pumps has been the subject of considerable attention over the last decade. The commercialization of precision pumps has allowed the creation of highly accurate fluid delivery systems, which have been widely employed in the fields of chemical engineering and medicine. In medical applications, advancements have gradually shifted toward the development of precision pumps with ultra-low flow rates. To achieve precise but controllable liquid delivery, conventional infusion pumps use servomotors as their actuators. Although servomotors are capable of extremely high levels of precision, their complex mechanical components and costly control circuitry render these systems uneconomical. More, applications are limited by its heavy weight and large size. Numerous new applications, however, such as homecare and emergency rapid-transfusion heating systems, do not require the high accuracy of servomotor pumps; rather, the weight and cost of the servomotor pumps limits the scope of their application.

Compared to traditional servomotors, micropumps have the advantages of small size and lower cost. Though there are many types of actuators and working principles, some of them are not suitable to medical applications. They can be sorted as electromagnetic [1,2], piezoelectric [3–5], shape memory alloy [6], electrostatic [7], thermo-pneumatic [8] and dynamic pumps, which are typically represented by electro-hydrodynamic [9] and magneto-hydrodynamic [10,11] pumps. Micropumps of shape memory alloy or thermos-pneumatic design may heat and influence the delivered liquids because heating is required to induce a volume change of pump chamber. Thus, electromagnetic and piezoelectric devices are major actuators for commercial products. Moreover, piezoelectric device has the advantages of a relatively simple structure and lower power consumption. These features are preferred for precision liquid delivery with low cost and weight.

Another challenge must be overcome before piezoelectric micropumps can be extensively applied in the medical fields. Specifically, such products feature disposable flow channels to prevent infection and contamination. In addition, the actuators and other parts of micropumps are easily separable, enabling the rapid replacement of used or damaged flow channels. However, most piezoelectric micropump designs feature an actuator integrated with the pump chamber, where the base of the piezoelectric component is bonded directly to the top of the diaphragm on pump

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Nomenclature

B_r	Bossed ratio
C_{ad}	Adhesive force coefficient
d	Thickness of the diaphragm
d_{ac}	Distance between the piezoelectric actuator and the top of diaphragm
t	Thickness of the valve
D	Flexural rigidity of circular plates
E	Young's modulus of the diaphragm
f	Frequency of an input AC
F_{ad}	Adhesive force act on the diaphragm by the fluid
F_e	Elastic force induced by the deflection of diaphragm
F_v	Force required to open the valve
h_c	Height of the residual liquid under the central area of a bossed diaphragm
h_p	Depth of a pump chamber
H	Pump head of the micropump
K_{eff}	Equivalent stiffness coefficient
r_a	Radius of the pump chamber
r_b	Radius of the bossed area
Q	Flow rates of the micropump
ν	Poisson ratio of diaphragm
y_c	Displacement of the center of a bossed diaphragm

chamber. Consequently, instead of simply discarding the chamber and retaining the more costly piezoelectric actuator, the entire pump must be discarded once it has been used. Therefore, developing a piezoelectric actuator in which the actuator can be separated from the pump chamber is necessary to reduce costs and avoid wastage.

Ha et al. [12] developed a separable thermo-pneumatic micropump in which the actuator, a glass-based heating chip, can be used repeatedly, and the PDMS chip is disposable. In addition, a separable piezoelectric micropump with a peristaltic design was proposed [13]. The control circuit and cascade chambers of a peristaltic pump system incur a higher level of cost than pumps with a single chamber. Although different types of separable micropumps have been developed, those with a single chamber and a simple structure, aimed at applications requiring low cost and disposability, are rarely discussed.

In our previous studies [14–16], compact piezoelectric diaphragm pumps with simple structures and high flow rates have been successfully developed for water cooling applications. Based on a similar actuator, this study is aimed to fulfill the requirements of medical liquid delivery. A piezoelectric micropump design with a separable pump chamber and actuator is proposed. The proposed micropump can operate at low frequencies, and the chamber can be independently discarded to reduce costs in fields such as healthcare and medicine.

2. Development of separable piezoelectric micropump

2.1. Challenges presented by separable piezoelectric micropump design

To achieve an affordable and convenient separable pump design, the integration of the actuator and diaphragm fundamentally differs from previous designs. The end of the piezoelectric module is not bonded to the diaphragm in order to simplify the separation of the chamber from the actuator. However, this decision also imposes a new challenge at the operational stage. Piezoelectric pumps operate in two stages, namely, the discharge stage and the suction stage. During the discharge stage, the actuator presses on the diaphragm, reducing the volume within the fluid-bearing chamber. Through the use of an effective valve module, most of the fluid within the pump chamber is discharged in a single direction. The suction stage commences immediately after the discharge stage. This involves the diaphragm being raised. In conventional pumps, because the diaphragm is bonded to the piezoelectric actuator, it is raised together with the actuator, thus drawing fluid into the pump chamber. The discharge and suction stages cycle continuously to generate an oscillating flow. Fig. 1 compares the operation of a conventional piezoelectric pump with that of the proposed separable piezoelectric pump. In contrast to a conventional piezoelectric pump, the diaphragm of a separable pump is not bonded to the actuator. Therefore, the diaphragm must rely on its own elasticity to return in the suction stage. If the resilience of the diaphragm is inadequate, it may take a relatively long time for the diaphragm to return to the equilibrium position, that is, the position of the diaphragm before the impact of the actuator in the discharge stage. The diaphragm can even become attached to the bottom of the chamber, causing performance degradation or even failure. Thus, the development of a diaphragm with an adequate equivalent stiffness is critical to the design of a separable pump, such that the diaphragm can be pressed by the actuation unit but also return to the equilibrium position to complete an operation cycle.

2.2. Design of separable piezoelectric micropump

Fig. 2 shows the proposed separable piezoelectric micropump. The pump can be separated into two parts, the reusable part and the single-use part. The reusable part contains the actuator and clamp layer, and the single-use part contains every component that may contact with the working fluid. Thus, the risk of contamination and infection can be reduced while the application cost is affordable due to the repeated use of the costly actuator.

2.2.1. Bossed diaphragm

To fulfill the aforementioned requirements of diaphragm in Section 2.1, the present study deviated from conventional flat-type diaphragm designs by employing a cylindrical transfer column diaphragm design. This design is referred to as a "bossed diaphragm." As shown in Fig. 3, the cylindrical protrusion not only facilitates the contact between the diaphragm and the piezo actuator, but also serves as a rigid center area. To characterize the diaphragm, the authors defined a dimensionless parameter, called the "bossed ratio" (B_r), to represent the ratio between the radius of the bossed area r_b and that of the pump chamber r_a (values range between 0 and 1).

$$B_r = \frac{r_b}{r_a} \quad (1)$$

Compared to a flat diaphragm, the bossed diaphragm offers increased stiffness without any modification to the overall thickness of the diaphragm d. According to Eq. (2) in Section 2.3.1, the equivalent stiffness will rise with the increasing of the radius of the bossed area r_b. In addition, the use of the bossed design reduces wrinkling of the diaphragm during installation, which is a common problem in pumps with flexible diaphragms. It is difficult to avoid any non-uniform stress on diaphragm when clamped between two structures. For a diaphragm with low stiffness, the stress may induce wrinkles and makes an influence on the equivalent stiffness. The behavior of a corrugated diaphragm is different from the original flat diaphragm and the equivalent stiffness may become higher or lower [17], thus increasing the difficulty in predicting the performance of the pump. On the other hand, the bossed diaphragm facilitates the installation. The stiffness can be increased by using the bossed design. Further, the thick central protrusion area can be considered a center rigid area without wrinkles. Thus, the bossed