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Deflection behavior of a piezo-driven flexible actuator for vacuum micropumps

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ABSTRACT

This paper proposes the development of a piezo-driven flexible actuator that creates displacement to drive a vacuum micropump. This actuator consists of parallel flexible amplification mechanisms and piezoelectric actuators. The flexible mechanism relies on its own deformation to amplify the displacement of the piezoelectric actuators. An elastic model is established to estimate the deflection behavior and the effects of its geometric relationship. The finite element method is employed to validate the design and analysis. An experimental investigation is performed to study the deflection and negative pressure. Conclusion is reached that the deflection of the flexible actuator is sensitive to the initial incline angle of the bridge arm. The displacement amplification ratio is not related to the material. An increase in compliance of the flexure hinges can improve the deflection behavior. The proposed actuator produces a displacement of 12.6 μm at a voltage of 54 V. The central rotational symmetry with multiple linkages increases the robustness against radial parasitic displacement.

1. Introduction

The development of micropumps has attracted considerable attention over the last decade. The commercialization of micropumps has allowed the creation of fluid delivery systems, which presents great potential in the fields of microanalysis, drug delivery, biological and chemical analyses, and miniature robots [1–4].

A small vacuum micropump makes possible the realization of miniaturized analytical instruments such as micro mass spectrometers and micro gas chromatographs [5]. Several vacuum micropumps were developed and fabricated as stable vacuum sources in 2014. An et al. [6] investigated two-part architecture for a Knudsen vacuum pump that utilizes thermal gradient to induce gas streams in the microchannel. By increasing the number of stages integrated in a monolithic silicon chip, this vacuum pump with 163 stages achieved a high compression ratio and reliable pressure over a long duration. Grzebyk et al. [7] presented a glow-discharge ion-sorption vacuum micropump, which utilizes avalanche ionization effect to maintain vacuum in the micropump chamber for hours. These types of vacuum micropumps satisfy the specific requirement of micro-scaled microelectromechanical systems (MEMS) devices.

Among the developed micropumps, the mechanical displacement valveless micropumps with vibrating diaphragms have been widely studied because they have a simple structure and quick response [8]. Schabmueller et al. [9] proposed a valveless micropump with a piezoelectric film, which had a maximum back pressure of 1 kPa only. Because the flow in a micropump is actuated by the vibratory diaphragm, the deformation displacement of the diaphragm plays a key role in the vibration. Improvement in the deflection behavior of the diaphragm is an optimal solution to promote the performance of a micropump [10,11]. In precision engineering applications, a flexible amplification mechanism is used to amplify the small displacement, which is one promising strategy to overcome the limitation of the small displacement. Ham et al. [12] designed a hinge–lever amplification mechanism with a displacement amplification ratio of up to 12 times. The micropump with this amplification mechanism has maximum back pressure of 6.8 kPa at a voltage of 100 V. Wang et al. [13] proposed a folded compliance mechanism as a vibrator of a valve micropump. Driven by a sinusoidal voltage of 400 Vpp at 490 Hz, the micropump achieved a maximum deflection of 355 μm and back pressure of 22.5 kPa.

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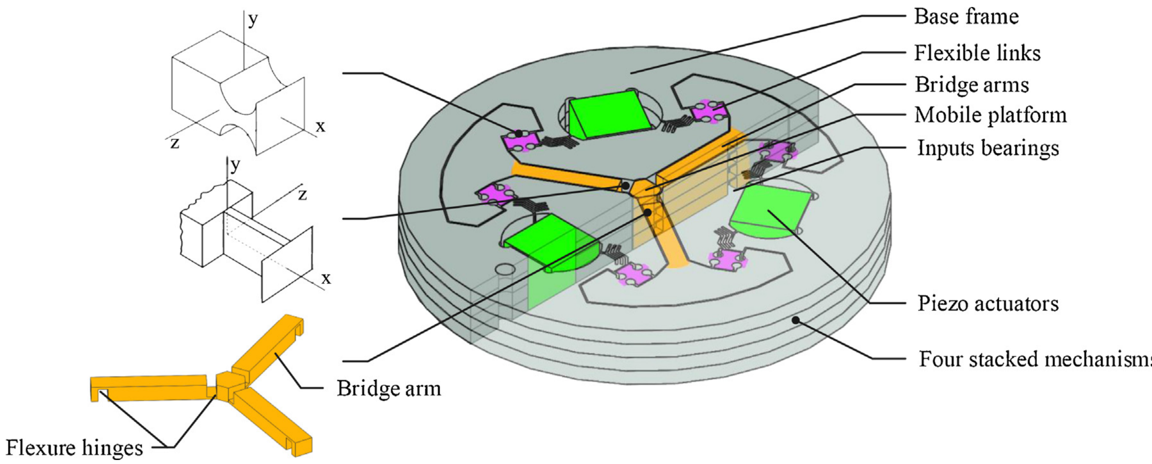

Fig. 1. Schematic diagram of the flexible actuator.

Pan et al. [14] utilized double flexible metal beams as a vibrator to enlarge deflection. The film micropump created maximum back water pressure of 29.7 kPa when driven by a square-wave voltage of 400 Vpp at 445.5 Hz. Moreover, Qu et al. [15] proposed a film micropump that integrated a monolithic flexible amplification mechanism as a vibration actuator, and it realized maximum back pressure of 80 kPa. These micropumps sacrificed their volume and easy fabrication to improve the pressure characteristics at the outlet of the micropumps. However, the study on vacuum micropump is for improvement in the pressure characteristics at the micropump inlet.

The flexible mechanism exhibits excellent performance in terms of deflection behavior, which is superior to the traditional mechanisms widely used in the applications of the nano-positioning stage and micro manufacturing [16–18]. Bhagat et al. [19] proposed a flexure-based three degrees of freedom (DOF) mechanism driven by three piezoelectric actuators. The pseudo-rigid body method was used to provide a solution to the minimization of the coupling effect in terms of mechanical topology. Qin et al. [20] proposed a decoupled XY stage in which a feedforward–feedback compound controller was employed to improve the tracking performance. Pinskier et al. [21] developed a bridge-type mechanism as a compact modular with a single DOF. The proposed modules can be serially coupled to form a micro manipulator with multiple DOFs.

The bridge-type mechanism is defined as a monolithic structure that relies on the deformation of flexure hinges to generate smooth displacement and a force in the normal direction. Compared with other flexible amplifiers [22,23], the bridge-type mechanism has excellent features, including a large displacement amplification ratio, high natural frequency, and compact size [24]. Ma et al. [25] developed an analytical approach to characterize and estimate the displacement amplification characteristics of a bridge-type mechanism based on the elastic-beam theorem.

The objective of the present study is to propose a flexible actuator as a vibrator for a vacuum micropump, which generates negative pressure for the adhesion mechanism of a miniature climbing robot. An elastic model is developed to investigate the effects of its geometric relationship on the deflection behavior. The central rotational symmetry with multiple linkages is a developed solution to estimate the radial parasitic displacement according to inverse kinematics. The design and performance are verified using finite element method (FEM) simulation and experiments. The proposed actuator is a parallel mechanism driven by three piezoelectric actuators, and it is capable of producing a normal displacement with no radial parasitic motion. Its advantages include a compact size, a large displacement amplification ratio, and a high natural frequency.

In this paper, Section 2 describes the design and principle of the flexible actuator. Considering the deflection behavior, including the normal deflection and radial parasitic displacement, the analyses are presented in Section 3. Section 4 introduces the fabrication procedure of the proposed flexible actuator. Details about the simulation and experimental evaluation are presented as results and discussion and given in Section 5. Conclusions are drawn in Section 6.

2. Design of flexible actuator

The design of the flexible actuator is inspired by the bridge-type and multi-linkage mechanisms. The schematic view of the developed flexible actuator is shown in Fig. 1. It is composed of three piezoelectric actuators and a mechanical body stacked using four identical flexible mechanisms. According to the displacement transmission, the flexible mechanism is further divided into the following: a base frame, flexible links, bridge arms, input bearings, and a mobile platform. The flexible mechanism employs two types of flexure hinges and a bridge-type mechanism with three bridge arms.

In the flexible mechanism, three slots are available for the installation of the piezoelectric actuators with a separation angle of 120°. Each slot is separated from the bridge arm at an angle of 60°. The central rotational symmetry increases the robustness against radial parasitic displacement.

The bridge-type mechanism amplifies the deformation of the piezoelectric actuator to achieve a large normal displacement. The flexible multi-linkage mechanism transports the parallel inputs and eliminates the parasitic displacement in the radial direction. Fig. 2 shows the deformation of the flexible mechanism responding to the inputs. Through flexible linkage *CD*, the displacements are coupled and transported to bridge arm *AB*. Finally, the mobile platform generates a corresponding normal displacement as output.

3. Analysis of deformation displacements

For the developed flexible actuator, the deformation displacements are composed of the normal and radial parasitic displacements. To design a flexible actuator that can achieve a normal displacement, performing further analysis would be helpful, assuming that the deflection is small. Generally, the displacement