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Development and analysis of a bridge-lever-type displacement amplifier based on hybrid flexure hinges

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ABSTRACT

Bridge-type mechanism is one of the most widely used displacement amplifiers in micro scale applications due to its compact and symmetrical structure. However, a drawback of the bridge-type mechanism that restricts its further applications is the limited amplification ratio. To solve this problem, a bridge-lever-type displacement amplifier is developed and analyzed in this paper. Compared with the conventional design, the proposed amplifier not only maintains a compact and symmetrical structure, but also features a high amplification ratio and high load capacity. To reduce the displacement loss of the amplifier and enhance its load capacity, the hybrid flexure hinges are employed in the novel design. Furthermore, the kineto-static model based on the compliance matrix method and the dynamic model based on Lagrangian method are established to analyze the bridge-lever-type amplifier. Finally, a prototype is fabricated whose amplification ratio is approximately 48 and 34 in the case of zero load and 30 N load respectively, which is confirmed by FEA simulation and experimental study.

1. Introduction

Compliant mechanisms are frequently used in precision engineering [1–3], where piezoelectric stack is a widely employed actuator due to its outstanding features, e.g., high stiffness, high resolution, and large blocking force. However, in general, the stroke of the piezoelectric stack is only about 0.1%–0.2% of its length [4–6], which is difficult to satisfy the application when a large workspace is required. To increase the effective actuation stroke of the piezoelectric actuators, many kinds of displacement amplifiers were proposed and developed.

The widely used displacement amplifiers are the lever-type amplifier and the bridge-type amplifier, as shown in Fig. 1. The former is well known for its simple and flexible structure, so the multistage lever-type amplifier is easily to develop [7–10]. Therefore, the lever-type amplifier is an appropriate candidate when a high amplification ratio is required. However, the amplification ratio of the lever-type amplifier depends on its lever length, thus the size of the amplifier with a large amplification ratio will be large, which is adverse to space-saving applications. In contrast, the bridge-type amplifier is superior in its compact and symmetrical structure especially in the case of large amplification ratio [11–13]. Fig. 2 shows the enveloping area comparison among the three amplifiers with amplification ratio 10 when the same piezo actuator is employed, where the bridge-type amplifier is the most compact design. However the amplification ratio of the bridge-type amplifier is hard to be large due to the limited amplification ratio phenomenon [11,13], for example, the amplification ratio of the bridge-type amplifier is always lower than 20, as shown in Fig. 3. Therefore, to design an amplifier featuring both compact structure and large amplification ratio is a great challenge in the field of displacement amplifier research.

To obtain a displacement amplifier with symmetrical structure and large amplification ratio, researchers paid more attention to the improvement of the bridge-type structure. Kim [14] developed a 3-D bridge-type mechanism with an amplification ratio of 10, which essentially is a serially connected two-bridge-type mechanisms. Muraoka [15] proposed an array-type design based on the “honeycomb link mechanism”, which effectively contributed to the compactness of the amplified actuator. Wulfsberg [16] designed a planar two-stage compliant mechanism with an application to the feeding units, which utilized three compound bridge-type amplifier with two individual actuators. Schultz [17] designed a multilayer nested rhomboid whose topological structure can be considered as an expansion of the 3-D bridge type mechanism. Xu [18–20] designed a variety of micro-positioning stages based on the bridge type amplifier. Regarding to the lever-type mechanism, Chen [21] demonstrated a two-stage lever type

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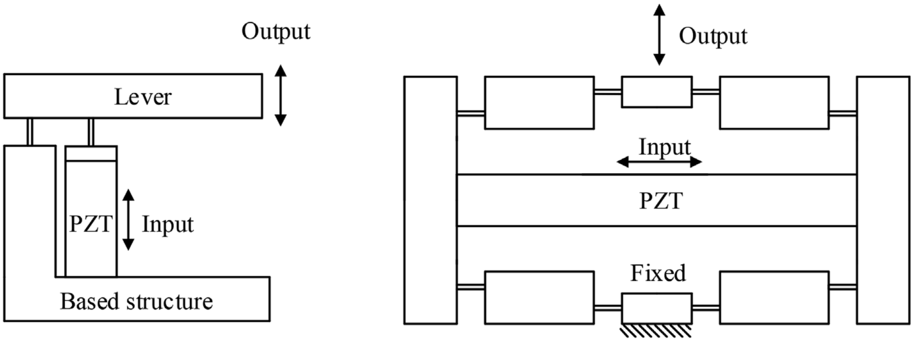
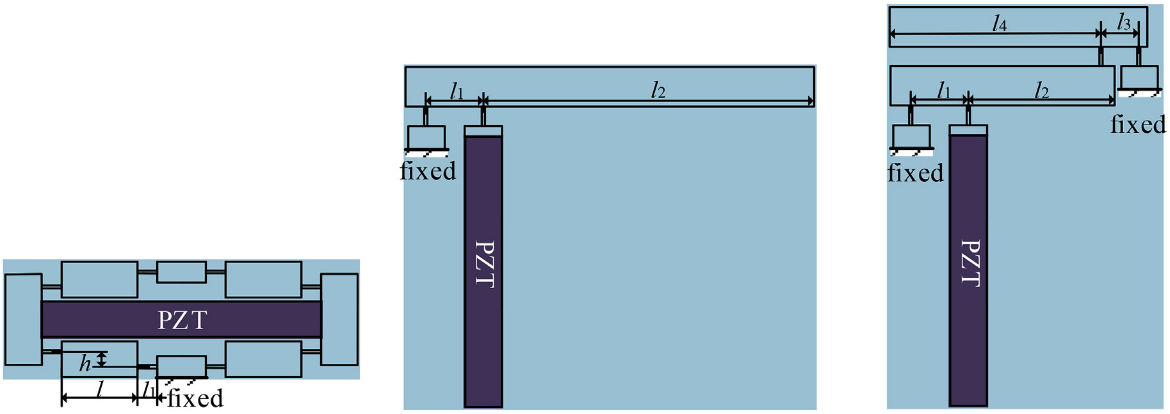


(a) Lever type amplifier (b) Bridge type amplifier

Fig. 1. Schematic of the two types of amplifiers.



(a) brige type amplifier (b)single stage lever type amplifier (c) two-stage lever type amplifier

Fig. 2. The comparison of the enveloping area of the three amplifiers.

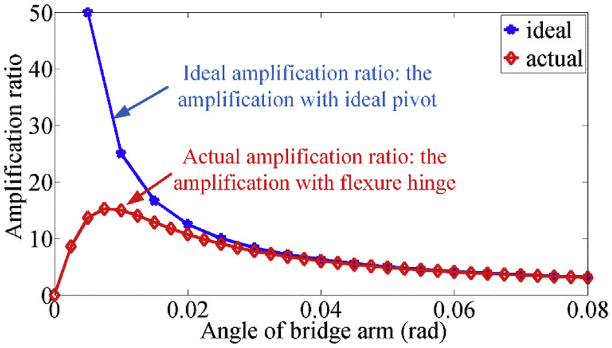


Fig. 3. The limited amplification ratio of the bridge type mechanism.

amplifier with an amplification ratio of 33.4, which can avoid the potential buckling problems because all the flexure hinges are loaded in tension. Tang [22] proposed a bio-manipulation used lever displacement amplifier with an amplification ratio of 30.6. Choi [8] presented a symmetric two-stage lever-type amplifier to amplify the stroke of the piezoelectric actuators. In summary, it is hard to address concerns on both the compact size and the large amplification ratio simultaneously from the previous designs. Moreover, the load capacity of the displacement amplifier is not drawn enough attention.

Except the challenges discussed above, the displacement loss is also a prevailing problem among almost all the compliant displacement amplifiers, especially for the design with a large amplification ratio [7,21–23]. Actually, the flexure hinges are generally considered as a replacement of the rigid joints to eliminate the backlash in the mechanism system. However, the stiffness introduced from the flexure hinges and the parasitic deformation of the flexure hinges will significantly influence the performance of the compliant mechanisms. Taking the lever-type amplifier as an example, the flexure hinge will suffer from extremely huge axial force which will result in non-ignorable axial deformation. According to the lever principle, the axial deformation will cause displacement loss $_{\Delta}l$ at the output end, as shown in Fig. 4. To suppress the displacement loss of the designed amplifier, the hybrid flexure hinges method [24] will be employed in this paper, which will be verified beneficial to reduce the displacement loss and enhanced the load capacity of the amplifier.

The rest of this paper is organized as follows. The design procedure of the bridge-lever-type amplifier is presented in Section 2. After that, the static and the dynamic models are established in Section 3. Also in this section, the maximum stress is analyzed. In Section 4, the proposed amplifier is analyzed applying the established modelling. Then in Section 5, the proposed amplifier is validated by FEA simulation and experiment study. Finally, Section 6 concludes this paper.

2. Mechanism design

The aim of this paper is to design a displacement amplifier that features compact structure, high amplification ratio and high load capacity simultaneously. In view of this point, the structure of the amplifier should be reconsidered and the design detail is demonstrated as follows.

Fig. 5 (a) shows the working principle of the conventional bridge type mechanism. The amplification ratio produced by the bridge type amplifier with ideal pivots can be calculated by the equation in Ref.