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Research paper

Topology optimisation of bridge input structures with maximal amplification for design of flexure mechanisms

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ABSTRACT

Bridge structures are one of the two most common design elements for providing input from stroke-limited piezoelectric actuators to flexure based mechanisms for micro/nano positioning and manipulation. However, the amplification achieved by such structures is dependent on both the element geometry and the load provided by the driven mechanism. In this paper, bridge-type structures are developed which maximise the output displacement using topology optimisation, and the variation of the geometry due to changing mechanism stiffness is studied. Cost functions defined to consider the input-force to output-displacement stiffness, as well as the effective displacement due to input-stiffness losses are developed. The structures found differ substantially from the bridge designs typically employed, particularly the symmetry assumed for such designs. Furthermore, it is shown that the choice in principal output direction has a substantial impact on the achievable displacement. The results of the analysis are used to formulate a bridge structure template which can be employed within standard heuristic design methods.

1. Introduction

Compliant mechanisms, those which employ flexure hinges and cantilevers in lieu of traditional pinned revolute and prismatic joints, allow the generation of continuous motions free of friction and backlash, require less maintenance and lubrication, and can exhibit higher degrees of repeatability due to the possibility of monolithic construction. The range and bandwidth of these mechanisms are related to the stiffness of each flexible element, and thus can be easily modified though selection of geometric parameters, such as the element's minimum thickness. Consequently, compliant mechanisms are a common component of many technologies requiring ultra-high precision motion generation, such as scanning probe microscopes, mechanisms for nanoimprint lithography, precision manufacturing, cell manipulation, microgrippers and optical steering mechanisms [1–7].

As the applications of such mechanisms expand, there is an ongoing demand for designs with more degrees of freedom (DOFs), whilst placing more stringent performance requirements on factors such as dynamic modes, kinematics, and

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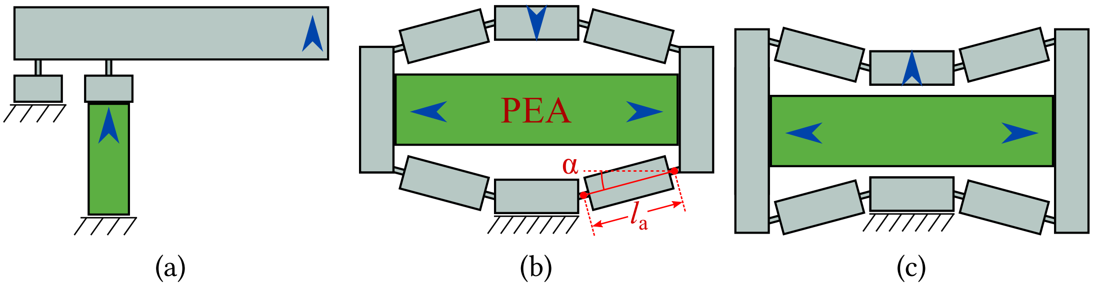

Fig. 1. Flexure based input structures for PEA driven mechanisms: (a) Lever amplifier, (b) Bridge element (downward configuration), (c) Bridge element (upward configuration).

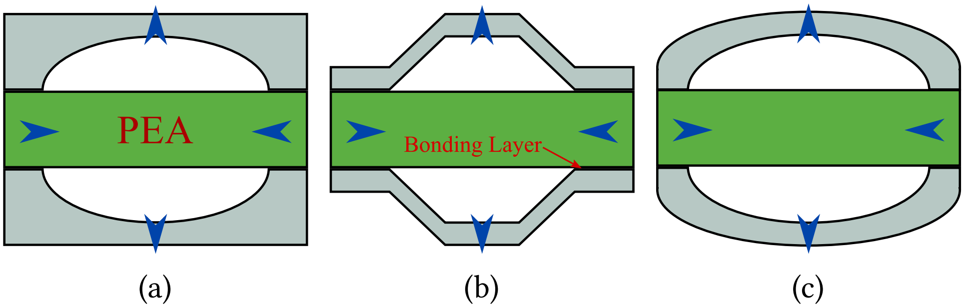

Fig. 2. Flextensional piezoelectric transducing elements: (a) Moonie element, (b) Cymbal element, (c) Rainbow element.

cross-coupling. As such, mechanisms have been proposed from linear and angular single-axis scanners, 2-DOF *XY* stages, and *XYZ* platforms, to those also capable of angular motion such as tilt-tip stages, $XY\theta$ stages and 6-DOF positioners [8–14].

Piezoelectric actuators (PEAs) are the most common choice to provide input displacements for these mechanisms. They consist of a stack of piezoceramic layers electrically connected in parallel. They are attractive due to their high stiffness, force output and bandwidth, with positioning resolution only limited by the capabilities of the driving electronics. However, PEAs also possess several important drawbacks which must be addressed within any high-precision positioning system. PEAs exhibit nonlinear behaviour such as drift and frequency-dependent hysteresis, where the latter can become a determining component (>50% of the full stroke) of the output even at moderate frequencies [15]. Consequently, much research has been devoted to modelling and feedforward compensation of the hysteresis, as well as robust feedback control strategies [16–19]. PEAs are also limited by their maximum stroke, typically in the 20–100 micron range, requiring more layers and physical size to achieve greater output. Finally, due to the nature of their construction, PEAs are fragile and must be protected from tensile or shear loads.

Due to their limited stroke, input structures including bridge and lever elements, such as those shown in Fig. 1, are almost always employed to amplify the input displacement. Whilst lever amplifiers can be used to achieve greater amplification ratios, improper design can expose the actuator to shearing loads. This necessitates the use of ball tips, which increase Hertzian contact losses, or added hinges at the input to decouple loads. In addition, lever elements typically require a large amount of space in comparison to the compact bridge structures. Alternatively, the symmetry of the bridge structure prevents shearing loads being applied to a PEA whilst occupying a region not much larger than the PEA itself. In particular, the symmetry of geometry and input forces ensures a purely vertical output motion under ideal conditions. There are also many types of bridge-like structures which have been utilised in the literature including the ‘moonie-type’, ‘cymbal-type’, and ‘rainbow-type’ transducing mechanisms, often used within ultrasonics and energy harvesting applications, which are shown in Fig. 2 [20–22]. Even within the same topology class, there have been many different ways such mechanisms have been implemented, and the choice of location and thickness of the compliant sections differs greatly.

The amplification of bridge structures has been studied extensively. Assuming a rigid body equivalent to Fig. 1 b, where the flexible hinges are replaced with ideal revolute joints, the amplification for infinitesimal inputs can be determined to be:

$$A_{\text{amp}} = \cot\alpha \tag{1}$$

This equation has been produced many times (albeit in slightly different forms) by many authors [23,24] The amplification can therefore be maximised under these conditions by letting the angle α approach zero. However, at the same time, the compliance of the structure is a factor in determining the amplification, and the output displacement is reduced. An analysis of the structure, incorporating the effects of hinge stiffness, was performed by Ma et al. [24], which produced this