Mechanism and Machine Theory 126 (2018) 201–209

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Design and experiment of a millimeter-range and high-frequency compliant mechanism with two output ports

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ARTICLE INFO

Article history:
Received 16 September 2017
Revised 26 March 2018
Accepted 5 April 2018

Keywords:
Compliant mechanisms
Flexure hinge
Piezoelectric actuator
Multistage amplifier
Precision positioning stage

ABSTRACT

This paper addresses a piezoelectric-actuated compliant mechanism with two output ports to provide tensile and compressive forces along with high dynamic motions for static tension and high-cycle dynamic fatigue testing of small-scale specimens or other precision flexible manipulation applications. A rhombus-type planar multistage displacement amplifier with a pair of guiding flexible beams is designed to realize a millimeter stroke while retaining high fundamental frequency. Improved effect of the guiding flexible beams on the vibration modes and attenuating impact on the output displacement are analyzed respectively by finite element analysis and theoretical kinematics modeling. A prototype is manufactured and the experimental performance evaluation shows a maximum stroke range of 1.44 mm (±720 µm) with the fundamental frequency of 628 Hz.

1. Introduction

At present, piezoelectric actuators have emerged as one of the most popular smart materials in modern precision applications owing to their unique merits of high resolution, large output force and fast dynamic response. However, major drawbacks of piezoelectric actuators are their very small stroke range and vulnerable to tension loads. For many applications where a large stroke or dynamic manipulation is required, flexure-based compliant mechanisms are often used to amplify the small stroke of piezoelectric actuators and/or used as a preload fixture to perform a dynamic task. With the advantages of no wear, no backlash, no friction and compact size, piezoelectric-actuated compliant mechanisms are increasingly applied in the state-of-art precision positioning stages for optical alignment, atomic force microscope, micro/nano-scale manipulation, precision machining applications, and so forth [1].

The aim of this paper is to design a piezoelectric-actuated compliant mechanism with two output ports to generate tensile and compressive forces with high dynamic movement for static tension and high-cycle dynamic fatigue testing of small-scale materials or precision devices such as micro-electro-mechanical systems (MEMS). The motivation is that with the development of experimental mechanics and research of new materials, *in situ* measurement of mechanical properties and observation of crack growth for small-scale materials or precision devices have attracted much attention around the world [2,3]. By conducting static tension and dynamic fatigue testing with the help of scanning electron microscope or metallographic microscope, micro-scale property and mechanical parameters can be accurately and comprehensively evaluated.

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https://doi.org/10.1016/j.mechmachtheory.2018.04.003

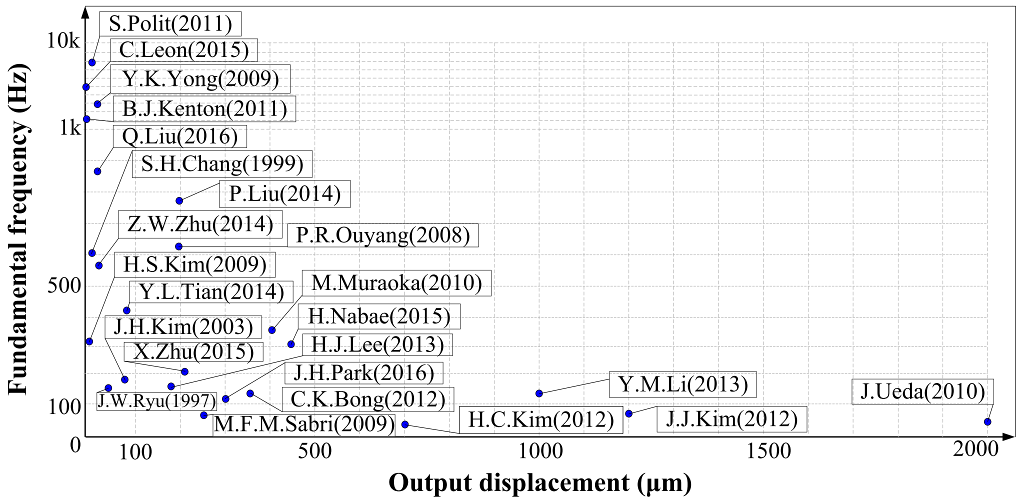

Fig. 1. Performance of compliant mechanisms or their composed precision positioning stages in literatures [8–31]. It should be noted that only one representative degree of freedom (DOF) of some multi-DOF stages was selected here.

In the past decades, extensive interests have been focused on developing instruments for small-scale tension/fatigue testing and a number of testing machines are commercially available. However, the present MEMS-based actuators [4–6] mainly offer micro/nano-scale displacements and forces. Actuators driven by the motor can provide a large stroke and force, but suffer from low frequency response; the friction and gap will also lead to poor precision. For tensile and high-cycle fatigue testing of small-scale materials and devices with a varying range of sample size from centimeters down to tens of micrometers, an actuator featuring millimeter stroke, high dynamic frequency and high precision as well as nano-scale resolution becomes necessitated to provide tensile and compressive forces along with high dynamic motions.

Compliant mechanisms transmit force and/or amplify the small strokes of piezoelectric actuators by the elastic deformation of their flexure hinges or flexible beams. It means the fact that large deformation range implies low resonance frequencies and low output stiffness, which limits the response bandwidth and control precision [7]. As a result, it is still challenging to design flexure-based manipulators with concurrently large stroke and high bandwidth due to the inevitable tradeoff between the deformation range and natural frequency of compliant mechanisms. Fig. 1 sums up the experimental output displacement and fundamental frequency of some typical compliant mechanisms or their composed systems at present [8–31]. It can be seen that either very large range or very high frequency can be realized separately, but it is difficult to concurrently maximize the two targets. Among these compliant mechanisms, rhombus-type mechanical amplifier is popular in engineering applications due to their large displacement amplification ratio with a compact size. To obtain large stroke, a three-dimensional two-stage rhombic compliant mechanism was proposed by Kim et al. [19]. However, the experimental output displacement was clamped to less than 10% of the original design. A nested three-dimensional rhombic multiplying compliant mechanism having over 20% effective strain was designed by Ueda et al. [10] but with low dynamic frequency. Besides, Secord and Asada [32] presented a variable stiffness actuator with tunable resonant frequency by adopting the nested multistage concept. Recently, a three-dimensional two-stage compliant mechanism with large amplification ratio was designed based on the concept of stiffness distribution [33]. These designs still suffer from the difficulty of concurrent large stroke and high resonance frequency. Additionally, assembly is needed in these mechanisms.

In this paper, we attempt to realize a millimeter range and relatively high resonance frequency larger than 500 Hz by designing a new compact planar multistage compliant mechanism with two output ports and without assembly. It can be used to generate tensile and compressive forces along with high dynamic movements for static tension/high-cycle dynamic fatigue testing or other precision flexible manipulation of small-scale devices. The remainder of this paper is organized as follows: design, finite element analysis and theoretical kinematics modeling are conducted in Section 2; experimental testing is reported in Section 3; finally, conclusions are drawn in Section 4.

2. Design and analysis

Picture of the prototype and working principle of the presented piezoelectric-actuated planar multistage compliant mechanism are schematically shown in Fig. 2. The compliant mechanism consists of two-stage rhombus-type displacement amplifiers. Output displacements of the two piezo-stacks can be multiply amplified twice. The mechanism was monolithically fabricated by electrical discharge machining technique with a whole size of 140 mm × 90 mm × 10 mm. Aluminium 7A04 was selected as the material for its large ratio of modulus to density and small input stiffness. Two identical piezo-stacks from PI Corp. were used as the force and motion generators and were installed into the compliant mechanism with a certain