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Optimal design of a piezo-actuated 2-DOF millimeter-range monolithic flexure mechanism with a pseudo-static model

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ABSTRACT

Flexure-based displacement amplifiers are frequently used to magnify the small stroke of piezoelectric actuators. In this paper, a hybrid rhombus-lever multistage displacement amplifier with an improved boundary constraint is proposed to develop a parallel millimeter-range XY monolithic mechanism while retaining a relatively high dynamic frequency. A concise pseudo-static model developed by the authors is utilized to analyze the kinetostatic and dynamic performances of the designed flexure mechanism and then the geometric parameters are optimized in terms of both kinetostatics and dynamics. Different from the previous Lagrange-based dynamic methods for compliant mechanisms, cumbersome calculations of the kinetic and elastic energies as well as adopting Lagrange's equation are all avoided. With the proposed pseudo-static model, the kinetostatics and dynamics of the flexure mechanism can be analyzed concurrently in a programmed statics-similar way, suggesting its superiority for fast performance prediction and parameter optimization during the early stage of design. Finally, a prototype of the XY monolithic mechanism is manufactured and experimentally tested for evaluating its performances. Experimental results show that the designed flexure mechanism has a motion range in excess of 1.2 mm × 1.2 mm with a resonance frequency of 128 Hz. The cross-coupling error is measured to be less than 2%, indicating an acceptable decoupling performance.

1. Introduction

At present, flexure-hinge-based compliant mechanisms have attracted widespread attention in a variety of scientific and industrial applications [1] including nano-positioning (Yong et al. [2], Li et al. [3], Tian and Shirinzadeh et al. [4]); micro gripping manipulation [5]; fast tool servo for precision manufacturing [6]; servo valve for fluid control [7], and so on. In those applications, there is an urgent need for manipulators with large motion range, rapid response, high precision and compactness. Traditional mechanisms with assembled rigid links, gears and joints cannot meet these demands due to their coarse resolution and poor precision caused by friction and backlash. On the contrary, compliant mechanisms of monolithic piece can provide highly accurate smooth motions through elastic deformation without wear, friction, backlash and no requirement of assembly.

As the most commonly used motion actuators in compliant mechanisms, piezo-stacks directly convert the electric potential to mechanical work and are desirable for applications where high accuracy, fast response and compact structure are

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demanded thanks to their fast frequency response, nano-resolution and large output force with a compact size, while other smart materials like magnetostrictive actuators that are also adopted for designing precision manipulators face the problem of bulky volume and need extra magnetic supply [8]. The largest disadvantage of the piezoelectric actuators, however, is their small strains (typically 0.1%). In view of this, compliant mechanisms are often designed to have the function of displacement amplification.

Flexure-based displacement amplifier can be classified as lever type and flextensional type with various flexure hinges like circular, corner-filleted and elliptic types, etc. From the early Moonie, Rainbow and Cymbal [9,10] to the current rhombus/bridge-types [11,12], Scott-Russell [13] and multistage mechanisms [14], plenty of displacement amplifiers have been developed. A lever-type amplifier has a large output displacement if there is no constraint on dimensions. Rhombus/bridge-types are popular in engineering applications due to their merits of large displacement amplification ratio with a compact size. However, traditional fixed-free boundary constraint limits their dynamic performance. In this paper, we adopt the free-free boundary constraint of the rhombus-type amplifier to explore its high output stiffness and good dynamic performance. Then, a compact multistage displacement amplifier with millimeter range and enhanced dynamic frequency is designed by combining the rhombus-type amplifier with a dual lever flexure, which is further used to develop an XY monolithic mechanism for precision positioning applications. As is well known, most of the present positioning stages have the motion range of hundreds of micrometers [1–5,15]. For large range and nano-resolution applications, one popular solution is connecting the macro stage serially with a micro platform [16]. One disadvantage of such macro-micro strategy is the bulky and complex structure. Moreover, several millimeter/centimeter-range monolithic manipulators were recently developed actuating by linear motors, voice-coil actuators and piezoelectric actuators [17–20]. However, some of these stages are still a little bulky with limited dynamic frequency due to the recognized trade-off between stroke range and dynamic frequency in compliant mechanisms that greatly hinders their applications for concurrently large workspace and fast dynamic response. The motivation of the design in this paper is to develop a compact XY flexure mechanism with the stroke range of more than 1 mm $\times$ 1 mm and resonance frequency as high as possible for applications in the scanning ion conductance microscope of large-scale specimen and rough surfaces.

When designing flexure mechanisms, kinetostatic and dynamic analyses are necessary and are much difficult in comparison to their rigid-body counterparts considering the fact that kinematic and elasto-mechanical behaviors are coupled in a flexure mechanism. The situation becomes worse for complex mechanisms with hybrid serial-parallel configurations and distributed compliance, in which elastic deformation of both flexure hinges and flexible beams should be included to ensure accuracy. Finite element package such as ANSYS can provide excellent solutions for the kinetostatic and dynamic analyses of flexure mechanisms with no constraint on geometry. However, the analysis procedure is time consuming for frequent iterations at the early phase of design where plenty of concepts should be calculated and evaluated in a short period of time. Therefore, since the pioneer works of mathematical modeling of flexure hinges by Paros and Weisbord [21] as well as the well-known pseudo-rigid-body model by Howell et al. [22], many analytically kinetostatic modeling methods have been proposed for designing compliant mechanisms [19,23–27].

For dynamic modeling of compliant mechanisms, previous methods mainly focused on the Lagrange-based models [3,28–32]. The general modeling procedure of these Lagrange-based methods is that the input/output stiffness of a compliant mechanism is first modeled by using a kind of kinetostatic methods; then the lumped-parameter dynamic model taking the motion degree of freedom as the variable is established by calculating the elastic and kinetic energies and using the Lagrange's equation [3,28–30]. On the other hand, a compliant mechanism can be discretized into sub-elements and a distributed-parameter dynamic model is built by Ryu's method [31] or finite elemental concept [32].

Therefore, another contribution of this paper is to extend our newly developed pseudo-static model [33] to accurately predict and optimize the static and dynamic performances of the proposed monolithic flexure mechanism. Differing from the previous dynamic modeling methods, kinetostatics and dynamics of a compliant mechanism can be concurrently modeled in a concise and programmed statics-similar way without calculating the elastic and kinetic energies either using Lagrange's equation.

This paper progresses as follows: Section 2 describes the configuration of the designed millimeter-range monolithic mechanism. Parameter optimization based on the pseudo-static model is performed in Section 3 followed by the experimental testing in Section 4. Finally, concluding remarks are provided in Section 5.

2. Design of the XY monolithic flexure mechanism

2.1. Comparison of different boundary constraints

Rhombus/bridge-type displacement amplifiers are popular in engineering applications due to their well property of large displacement amplification ratio and high output stiffness with a compact configuration. Fig. 1(a) illustrates a rhombus-type displacement amplifier with the traditional clamped-free boundary constraint. This type of boundary constraint was prevalently adopted in all kinds of previous compliant mechanisms [11,12]. Fig. 1(b) provides the boundary constraint by clamping one side of the input ports while the two output ports are free. Apparently, rhombus-type displacement amplifier with the traditional boundary constraint has one output port, while the latter has two output ports.