

A Piezo-Driven Compliant Nanopositioning Stage with Large Stroke for Micro/Nano Manipulation

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Abstract. This paper presents the design, analysis, and testing of a single-axis compliant nanopositioning stage with large stroke driven by piezoelectric actuator for micro/nano manipulation. In the developed stage, a hybrid displacement amplifier integrating two kinds of flexure-based input/output decoupling modules have been developed to achieve a large stroke and precise positioning. The analytical modelling and finite element analysis are given to validate the mechanical performance and a prototype of the proposed stage is fabricated for performance tests. The experimental results show that the developed stage has the travel stroke of 214 μm with a resolution of 8 nm. It is demonstrated that the stage can be adequate for micro/nano manipulation.

1 Introduction

Recently, compliant nanopositioning stages with a large stroke are frequently required in different fields of micro/nanomanipulation.[1, 2] Meanwhile, piezoelectric (PZT) actuators with nanometer resolution, excellent dynamic characteristics, small size, and high driving force have been usually employed in the nanopositioning stages.[3, 4] However, the drawback of the piezoelectric actuator is its limited travel range which are not suitable for requiring a large workspace.

Consequently, a lever-type flexure-based displacement amplifier is widely applied to amplify the limited stroke of PZT in many compliant nanopositioning stages.[5] While it can easily induce parasitic motion errors.[6] Another type of commonly used amplifier refers to bridge-type amplifier, which has compact size, symmetric structure and sufficient amplification ratio.[4, 7] Unfortunately, the nanopositioning stages based on bridge-type amplifier have relatively poor dynamics. In addition, due to a lateral displacement at the driving end of the stage increases with the increasing of the input displacement, a decoupling mechanism is needed for protect PZT from the lateral forces and bending torques.[8] Therefore, it is a challenge working to design a compliant nanopositioning stage possessing both low cross-coupling and large stroke simultaneously.

In this paper, a novel compliant piezo-driven nanopositioning stage with large stroke is proposed. A hybrid amplifier, which is composed of double flexure-based amplifiers, is developed to achieve a large stroke. In contrast with the commonly amplifier, the novel amplifier is characterized by compact size with large

amplification ratio, high dynamics and low cross-coupling.

Meanwhile, two types of compliant decoupling modules are developed to reduce the input and output couplings. Based on the configuration of the stage, the analysis models and experimental tests validate that the developed stage achieved the large stroke with nanoscale resolution, low input coupling and compact size. It is demonstrated that a considerable potential of the stage for the applications in various micro/nano manipulations.

2 Mechanical design

The novel compliant nanopositioning stage is shown in Fig.1. It is composed of a symmetrical flexure-based input decoupling module(ABCD), a hybrid amplifier(EFGH), a flexure-based motion guide module(IJKL), and a PZT actuator. Corner-filletted flexure hinges are used in the stage. The PZT actuator adopted in the developed stage can generate a nominal displacement of up to 38 μm at the maximum drive voltage of 100 V, and can provide a maximum driving force of 1000 N.

As shown in Fig.1(b), a hybrid-type amplifier, which is a combination of lever-type and bridge-type amplifier, has a compact size with a large amplification ratio and high dynamics. Meanwhile, due to the symmetric configuration, the amplifier can eliminate the lateral offset error of the output end and guarantee a precise linear output. A couple of input decoupling modules are both mounted between two sides of the PZT. It can reduce the lateral movement perpendicular to the PZT, and protect the PZT from lateral forces and bending torques. In addition, a motion guide module is integrated with the

moving platform can further ensure a precise positioning of the output end.

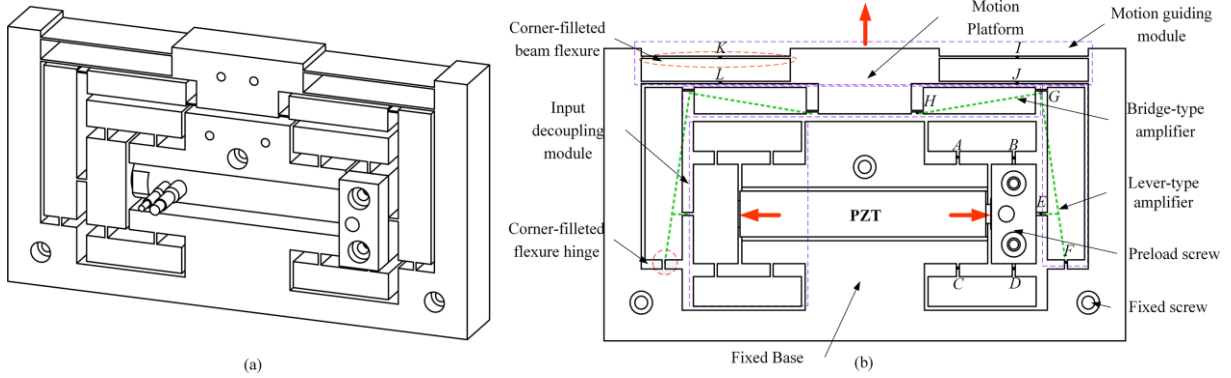


Figure 1. Developed Compliant Stage (a) 3-D Prototype and (b) Schematic Diagram

The motion of the nanopositioning stage is described as follows. When the PZT exerts on the stage, it results in the horizontal displacement of the input decoupling module, which is subsequently amplified by the lever-type and bridge-type amplifiers (EFGH), and in turn, to prompt a precise linear displacement of the moving platform by the motion guide module (IJKL).

3 Modeling and analysis

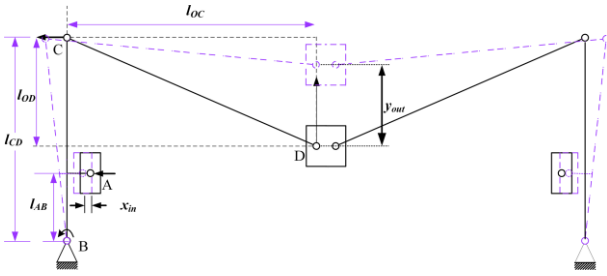


Figure 2. Kinematics of the developed compliant stage

The fundamental structure of the nanopositioning stage is a special five-bar linkage mechanism as illustrated in Fig.2. The input and output displacement are resented by x_{in} and y_{out} , respectively. The theoretical displacement amplification ratio R_{amp} of the DAM using geometric relations is defined as:

$$R_{amp} = \frac{2 \left(l_{OD} - \sqrt{l_{OD}^2 - \left(\frac{l_{BC}}{l_{AB}} x_{in} + 2l_{OC} \right) \frac{l_{BC}}{l_{AB}} x_{in}} \right)}{x_{in}} \quad (1)$$

According to Eq. (7), it can be seen that the stage has a constant amplification ratio, which only depends on the geometric parameters of l_{AB} , l_{BC} , l_{OC} and l_{OD} , but has no relations with flexure elements.

The static model of the compliant nanopositioning stage is based on the strain energy method.[9] For

Castigliano's second theorem, the total strain energy of the developed stage is

$$U = \sum_{i=1}^{10} \left(\int_0^{l_i} \frac{N_i^2}{2EA} dx_i \right) + \sum_{i=1}^{10} \left(\int_0^{l_i} \frac{M_i^2}{2EI} dx_i \right) + \sum_{i=1}^{10} \left(\int_0^{l_i} \frac{\alpha S_i^2}{2GA} dx_i \right) \quad (1)$$

where E is Young's modulus; A is the cross-section area of the flexure hinges; I is the inertia moment; G is the shear modulus. The normal force N_i , shearing force S_i and bending moment M_{bi} can be expressed by static equilibrium.

For strain energy method, the input displacement x_{in} , output displacement x_{out} , input stiffness of the stage can be obtained as, respectively

$$x_{in} = \frac{\partial U}{\partial F_{in}} = \frac{\delta}{\delta F_{in}} \left| \sum_{i=1}^{10} \int_0^{l_i} \left[\frac{N_i^2}{2EA} + \frac{M_{bi}^2}{2EI} + \frac{\alpha S_i^2}{2GA} \right] dx_i \right. \quad (2)$$

$$x_{out} = \frac{\partial U^*}{\partial F_{11y}^*} = \frac{\partial}{\partial F_{11y}^*} \left| \left(\sum_{i=8}^{10} \int_0^{l_i} \left[\frac{N_i^{*2}}{2EA} + \frac{\alpha S_i^{*2}}{2GA} + \frac{M_{bi}^{*2}}{2EI} \right] dx_i \right) \right. \quad (3)$$

$$k_{in} = F_{in} / x_{in} \quad (4)$$

It is known that a piezo actuator is compressed when a force is applied. Hence, the stiffness of the PZT and the stage must be taken into account when deducing the maximum output displacement of the stage and can be expressed as

$$x_{act} = \frac{k_{pzt}}{k_{pzt} + k_{in}} x_{pzt} R_{amp} \quad (5)$$

where k_{pzt} is the stiffness of the PZT, x_{pzt} is the maximum nominal displacement of the PZT.

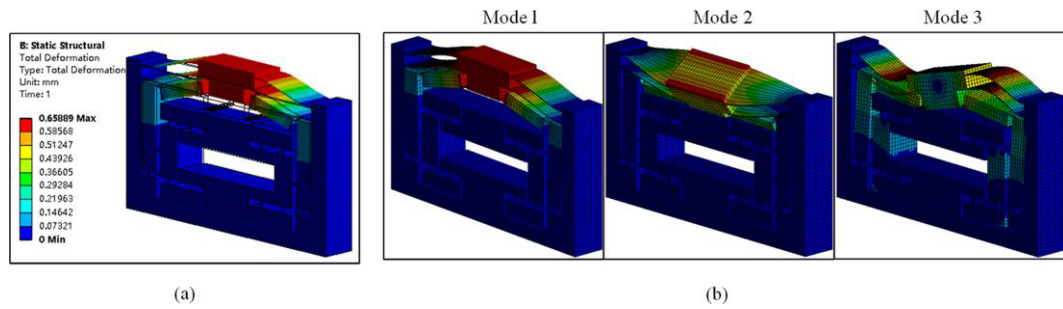


Figure 3. FEA results of (a) Deformation Behaviour and (b) Mode Shapers from 1st to 3rd

Fig. 3 shows the FEA results of the developed stage by commercial software ANSYS. The stage can generate an output displacement of 208 μm with the input displacement of 18 μm as shown in Fig.3 (a). Thus, it can be deduced that the proposed stage has a displacement amplification ratio of 12.1. And it can be inferred that the input stiffness of the stage is 28.2N/ μm and the output stiffness of the stage is 2.45N/ μm . In addition, the relevant maximum stress of 52 MPa is much smaller than the yielding stress of the material of aluminum alloy 7075. Fig.3 (b) demonstrates that the first three natural frequencies of the proposed stage are 202 Hz, 1161 Hz and 1410 Hz, respectively.

4 Experiment

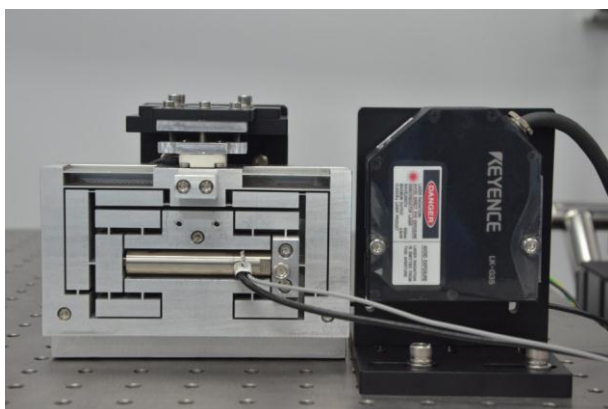
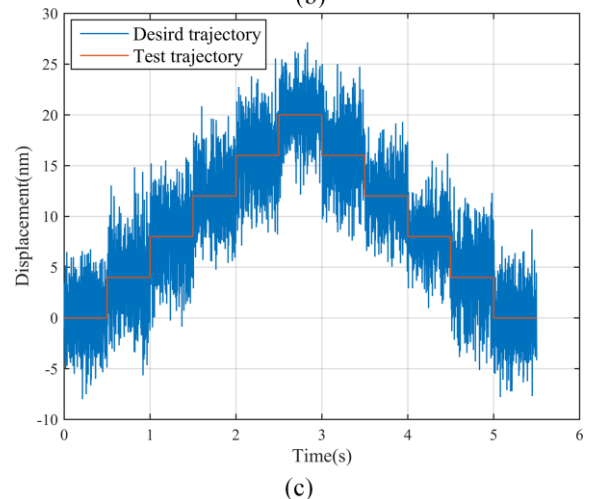
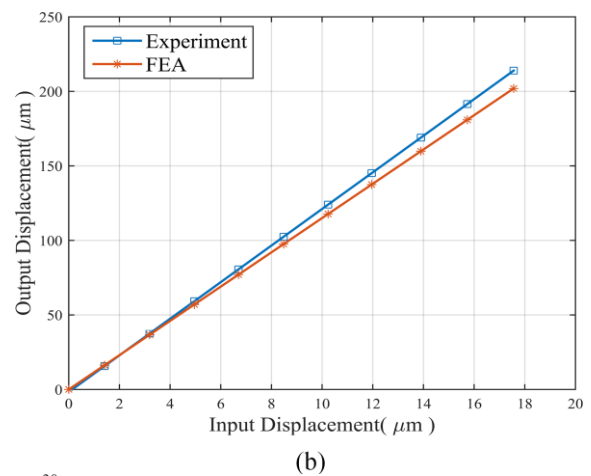
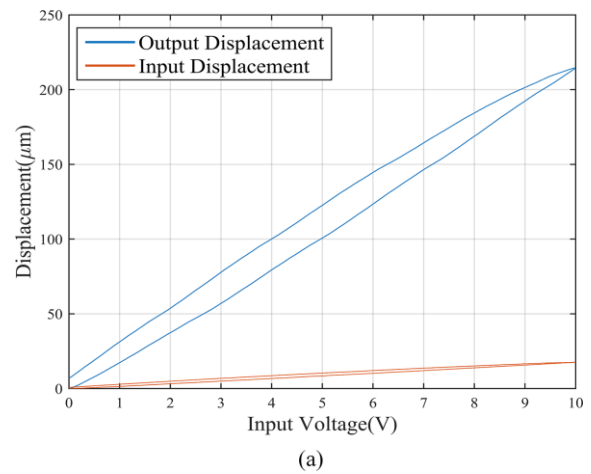


Figure 4. The Manufactured Nanopositioning Stage

Fig. 4 shows that a prototype of the proposed stage with compact size of 92 \times 18 \times 50 mm, which is fabricated using wire electrical discharge machining (WEDM) technique with Aluminum 7075. The positioning stage is driven by a piezo actuator (model: P-841.30, from Physik Instrument, Inc.) with a multi-channel PZT amplifier (model: E-501 from Physik Instrument, Inc.) providing driven voltage (0–100V) for the PZT. A capacitive sensor (model: 4810, from MicroSense) is integrated with the stage as a position feedback. A compactRIO 9022 from National Instrument Co. equipped with a 16-bit ADC/DAC is applied to carry out a real-time control for the proposed stage.



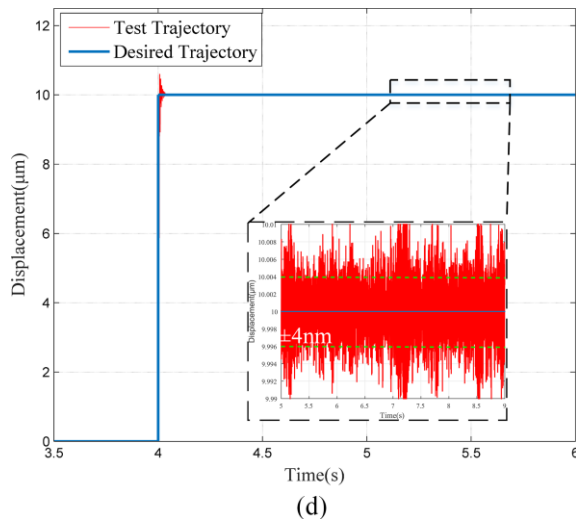


Figure 5. The Test Results of the Proposed Stage (a) Displacement for Input Voltage from 0 to 100V, (b) Amplification Ratio, (c) Resolution of 8 nm and (d) Stepwise Response of 10µm

As shown in Fig.5(a), when a 100 V voltage signal is provided to drive the piezoelectric actuator, the maximum input displacement of the stage is approximately 214 µm with respect to the input displacement of 17.7µm. The effective amplification ratio of 12.1 is shown in Fig.5(b).

Meanwhile, in close-loop positioning performance test, a minimum resolution of 8 nm is clearly attained as shown in Fig.5(c). Besides, Fig.5(d) shows a step response of 10 µm, which demonstrates that the stage has a rapid transient response (less than 30ms) and steady state error of ± 4 nm.

5 Conclusion

A piezo-driven compliant PZT-driven nanopositioning stage with large stroke is developed in this paper. To design an optimized prototype, we establish the kinematic model and perform the FEA validation. Finally, a prototype of the stage is fabricated to carry out the performance test of the stage. The test results show that the proposed stage with a minimum resolution of 8 nm

has a high amplification ratio of 12.1 and a maximum displacement of 214 µm. It demonstrated that the proposed compact stage is capable of utilizing in the field of micro/nano manipulations.

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