Design and Testing of a 2-DOF Flexure-based Compliant Stage

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Abstract. This paper presents the mechanical design and testing of a 2-DOF flexure-based compliant stage. The prismatic joints are first discussed. To obtain high resonance frequency and decoupled property, the stage composed of four parallel chains with symmetrical configuration should be employed. Finally, an experimental platform is set up to test the cooperative tracking performance. The experimental trajectory is in good agreement with the desired trajectory under various input frequencies. It shows that the maximum tracking error exhibits an increase from 0.8% to 2.7%. The experiment results demonstrate that the proposed compliant stage possess good tracking performance under 100 Hz, which also validates the reasonability of the stage.

1 Introduction

Flexure-based compliant mechanisms have many advantages, such as no clearance, no friction losses, no need for lubrication, compactness, and ease of fabrication [1-3]. Considering these advantages, they have been widely used in many industrial applications, such as scanning probe microscopy [4-6], micro-grippers [7-8], and biological science [9-10].

In the past decades, various flexure-based compliant stages have been developed. Awtar [11] presented a parallel XY flexure mechanism designs based on systematic constraint patterns. The advantages of the parallel flexure structure were discussed, and the constraint arrangement was given directly. Qin [12] designed a 2-degree of freedom (DOF) decoupled flexure-based mechanism which was composed of statically indeterminate symmetric flexure structures in parallel. The symmetric design helped to eliminate the thermal error and obtain decoupled property. The experiment results demonstrated that the proposed mechanism had good decoupled ability and load capability, and wide potentials in precision positioning applications. Yong [13] introduced a flexure-based XY stage for fast nanoscale positioning. The design of the flexure-based nanopositioning stage was based on the concept of flexible mechanisms. The stage was composed of two main parts: the outer section that consisted of amplification levers and circular flexures, and the inner section that included a stage and beam flexures. Li [14] designed a totally decoupled flexure-based XY parallel micromanipulator. The double compound parallelogram flexures and a compact displacement amplifier were employed, and they were simple and symmetric. Both finite element analysis and experiments could validate the decoupled property.

There have been many compliant stages with various good performances, such as decoupled ability, high resonance frequency and large workspace. Nevertheless, the design of these existing mechanisms is not systematic. Therefore, the present study addresses the design and testing of a 2-DOF flexure-based mechanism. The mechanical design is first introduced, and the experiments on cooperative tracking performance are tested. The remaining sections of this paper are organized as follows. In section 2, the mechanical design of the stage is derived. In section 3, a prototype of the stage is manufactured an experimental platform is set up. The circular tracking performance is subsequently tested under various input frequencies (from 20 to 100 Hz).

2 Mechanical design

Flexure-based mechanisms can be classed into two types: planar and space mechanisms. The planar flexure-based mechanisms have been applied most widely, and they are usually composed of several prismatic joints, such as linear, parallelogram and amplifying prismatic joints. A linear prismatic joint is illustrated in Fig. 1, and it is composed of flexure hinges, rigid beams and one output platform. The structure is symmetric about the output platform and both ends are fixed. Being symmetric, the output platform would rotate around the center point O when a moment M_z is applied. In addition, the output platform can translate along y-axis if the force F_y is applied to point O. The parasitic motions in x-axis and the parasitic rotations about z-axis can be attenuated by the symmetrical configuration. By contrast, it could remain static in conjunction with consideration of the high stiffness along x-axis when the force F_x is applied to point O.
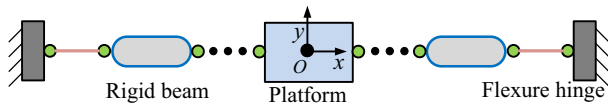
Figure 1. The linear prismatic joint

The parallelogram and double parallelogram prismatic joints are the common joints which can provide translational motion. To derive the decoupled property, flexure-based mechanisms are usually composed of double parallelogram rather than parallelogram. As shown in Fig. 2, the double parallelogram is composed of four limbs, and both sides of the joint are fixed.
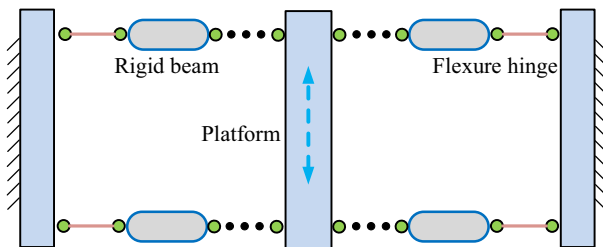

Figure 2. The double parallelogram prismatic joint

For a notch flexure hinge, there are strong couplings between the rotational and translational motions. Furthermore, the rotation center of a flexure hinge drifts whenever the hinge works, resulting in motion errors. To obtain decoupling properties, multiple flexure hinges can be combined to form certain structures. As illustrated in Fig. 3, the parallelogram prismatic joint can keep the orientation of the output platform invariant when the platform is actuated by the force F_x along x-axis. However, undesired cross-coupling error e_y along y-axis is generated at the same time. Compared with the parallelogram joint on one side, with a symmetrical configuration about the actuating axis, the double parallelogram prismatic joint can eliminate the coupling error completely, and thus it possesses output decouple property. In practice, the parallelogram joints are usually used as prismatic joints.
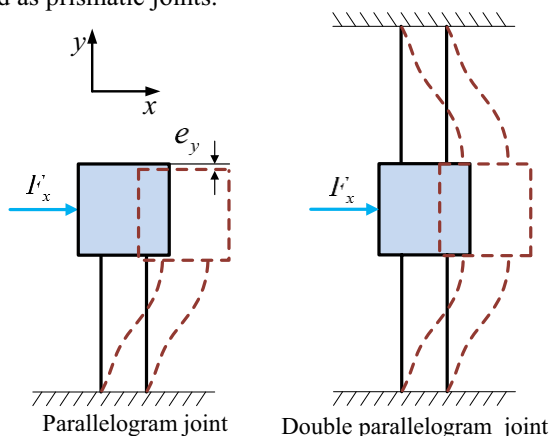

Figure 3. Parallelogram and double parallelogram joint

The amplifing prismatic joint is similar to the bridge-type displacement amplification mechanism. As shown in Fig. 4, surface D is fixed. There is a displacement output on surface C when imposing a force on surfaces A and B. Using this joint, the input

displacement can be amplified by more than ten times. Nevertheless, it is only used for compliant mechanisms with low resonant frequency.

In general, flexure-based mechanisms can be classified into two categories according to the kinematic structure: the serial and parallel mechanisms. Serial mechanisms are easier to design, and they have substantially decoupled degree-of-freedom. By contrast, parallel mechanisms with closed-loop kinematic features possess many advantages, such as high load carrying capacity, rigidity and accuracy.

According to the kinematic structure, the flexure-based micro-motion stages can be classified into two categories: the serial structure and the parallel structure. The parallel structure which possesses high rigidity, high load carrying capacity, and high accuracy could be selected. To derive high resonant frequency, the parallel structure should be employed, and the stages should be rigid and compact.

Flexure-based parallel mechanisms are usually built on 2-*PP*、3-*RRR*、3-*PPP* and 6-*SPS* parallel structure, where *P*, *R*, *U*, and *S* denote the revolute, prismatic, universal and spherical joints, respectively. To achieve 2-DOF motion, the 2-*PP* parallel structure could be selected. In addition, to achieve high precise motion, magnetic levitation motors, electromagnetic actuators, voice coil motors and piezoelectric actuators (PZTs) are usually employed. The PZTs are selected to drive the flexure-based compliant stage because they can provide fast and ultra-precision motions.
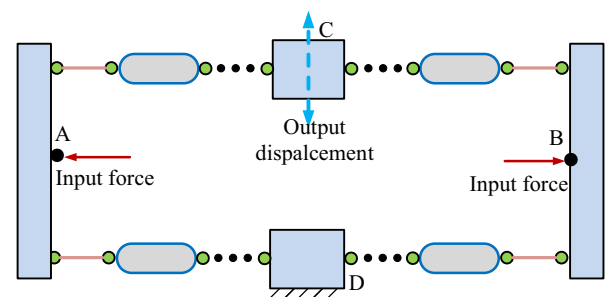

Figure 4. The amplifying prismatic joint

Meanwhile, to obtain decoupled property, the stage with symmetrical configuration should be employed, and thus it can be depicted as Fig. 5. It is composed of four parallel chains, and each chain consists of two prismatic joints. One joint P_1 is used to provide the forces actuated by the PZTs to the stage. The other joint P_2 is employed to transmit the forces and deformations of the flexure hinges to the output platform.

According to the analysis above, to obtain compact structure, P_1 and P_2 can be the linear and parallelogram prismatic joints rather than the amplifying prismatic joints. In addition, the parallelogram is virtually composed of several linear prismatic joints. Therefore, only the linear prismatic joints could be employed to form the stage.
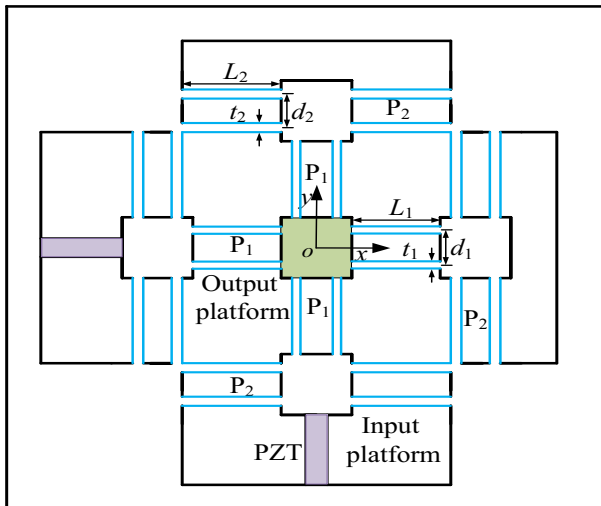
Figure 5. The flexure-based compliant stage

Notch flexure hinges can be manufactured by drilling or milling to form a circular, corner-filled or constant rectangular cutout. A flexure hinge is actually a complex spring element that can respond to and transmit both rotation and translation. The constant rectangular cross-section flexure hinge is selected because it is simple and easy to design. The prismatic joints P_1 and P_2 are composed of several flexure hinges, and their performances are easily influenced by their geometrical parameters. Thus, the parameters of the stage should be optimized.

The objective of the optimization is to maximize the resonance frequency. Meanwhile, the parameters are optimized to obtain the workspace of the stage which is above 18 μm. The thickness of the stage is chosen as 10 mm to guarantee the stiffness of the stage in z-axis. Meanwhile, the length and width of the output platform could be selected as 20 mm× 20 mm to install sensors and accessories. Considering the size of the PZTs, the input platform is chosen as 20 mm× 20 mm to connect to the mechanism and PZTs. The flexure hinge thickness t can be divided into n parts. According to the analysis in our earlier paper [15], the divided parts n are selected 2 to maximize the resonance frequency, and the optimized parameters are listed as follows: L_1=25 mm, L_2=28 mm, t_1=2.5 mm, t_2=3 mm, d_1=11.5 mm and d_2=11 mm.

3 Experiments

An experimental platform is set up. It includes a dSPACE-DS1107 board, two catalog-length gauges (MT 1281), two PZTs (PSt 150/7/40 VS12 from XMT Harbin, Inc.), a piezo amplifier and drive (XE500/E05 from XMT Harbin, Inc.), and the proposed flexure-based compliant stage. As illustrated in Fig. 6, the material of the stage is aluminum 7075. The two preloaded PZTs are actuated by the driver under control of the dSPACE board, with a voltage range of 0-120V. To realize the PI control, the displacements of the output platform are measured by two catalog-length guages (MT 1281 from Heidenhain, Inc.). To reduce vibrations, the air spring optical platform (1209M-100T) made in South Korea is employed.
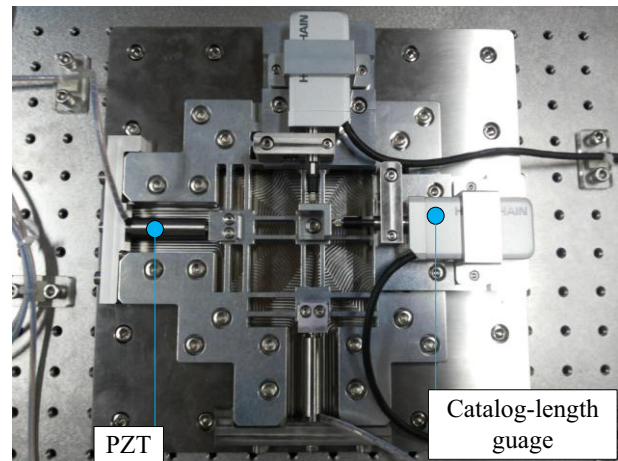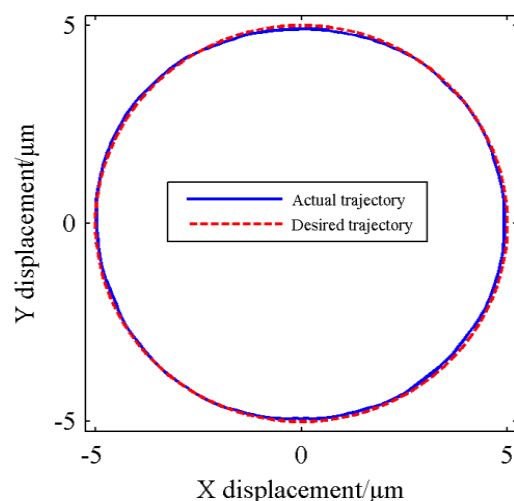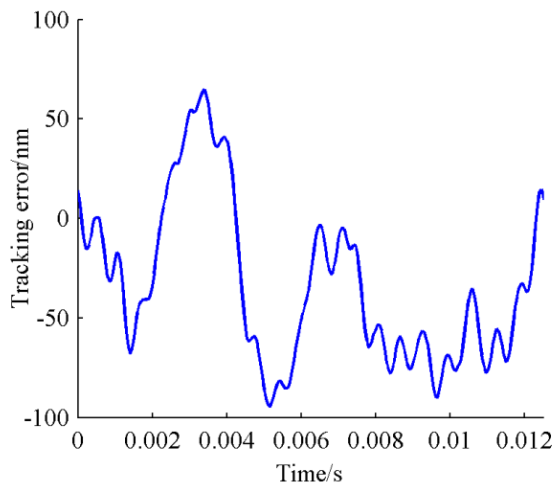

Figure 6. The experiment platform

The dSPACE board can be applied for receiving displacement feedback from the catalog-length gauges, calculating the control, and then sending the it to the amplifier and drive. The 16-bit analog to digital converters is used to translate the analog voltage positional signal to digital signals used by the PI controller. The amplifier and drive can be empoyed to receive command signals from the PI controller and provide amplified voltage to drive the preloaded PZTs.

To verify the proposed mechanical design of the compliant stage, the cooperative tracking performance is tested. A circular trajectory test is performed under different frequencies (from 20Hz to 100Hz), and the input circular radius is 5μm. The compliant stage can be actuated by driving it in x-axis and y-axis with the appropriate amplitudes and phase quadrature (shifted in phase by 90 degrees). Without loss of generality, only the circular tracking performance test under input frequency 80 Hz is illustrated in Fig. 7. It can be seen that the actual trajectory derived from experiments is in good agreement with the desired trajectory. The tacking error is less than 100 nm, and the maximum error is 2% in terms of the circular radius 5μm.

(a)   Tracking results

(b)   Tracking errors

Figure 7. Circular tracking performance under 80 Hz

The circular tracking error under various input frequencies is studied, as demonstrated in Fig. 8. The tracking error exhibits an increase with increasing the input frequency. To be more specific, the maximum tracking exhibits an increase from 0.04 μm to 0.135 μm. Considering that the input circular radius is 5μm, the maximum tracking error would be 2.7% under input frequency 100 Hz, and the minimum tracking error would be 0.8% under input frequency 20 Hz. Especially, the minimum tracking error would be 0.8% under input frequency 60 Hz. The experiment results indicate that the flexure-based compliant stage possess good cooperative tracking performances.
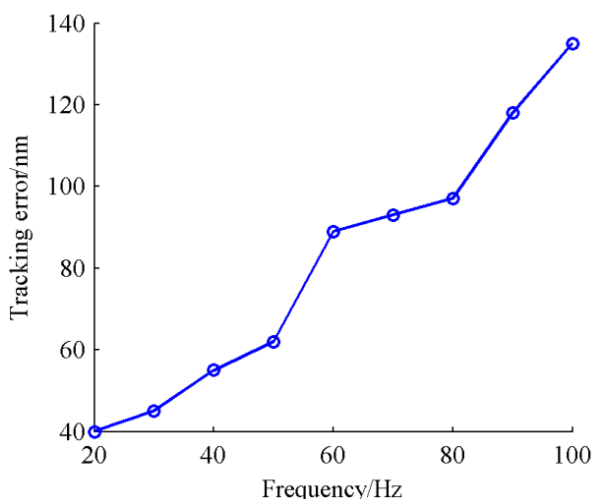

Figure 8. Tracking error under various input frequencies

4 Conclusions

This paper presented the mechanical design and testing of a flexure-based compliant stage with symmetrical configuration. The stage was designed based on the prismatic joints to obtain high resonance frequency and good decoupled property. The flexure parallel structure was selected, and it was composed of four parallel chains. Each chain consisted of two prismatic joints which were

composed of the constant rectangular cross-section flexure hinges. The optimization is carried on to maximize the first resonance frequency. Finally, a prototype of the stage is manufactured and an experimental platform is set up. And the circular tracking performance was subsequently tested. The experiment results indicated that the proposed flexure-based compliant stage possessed good tracking performance (from 20 to 100 Hz), which validates the reasonability of the design.

Acknowledgement

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