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Flexure-based dynamic-tunable five-axis nanopositioner for parallel nanomanufacturing

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ABSTRACT

With the increasing demand for devices and systems with nanometer precision in the modern manufacturing industry, tip-based nanofabrication (TBN) has become an indispensable part of manufacturing process. However, a common issue that needs to be addressed is to increase the throughput of TBN, which is sequential and inherently slow. To overcome the difficulty, in this paper we present the design and control of a flexure-based five-axis nanopositioner with dynamic-tuning capability for parallel nanomanufacturing applications. The dynamic-tuning method enables trade-offs between the range and speed of the nanopositioner so as to increase the throughput of the nanomanufacturing system. The experimental results indicate that the nanopositioner conforms with the in-plane range and resolution requirements, i.e., ±5 mm/100 nm in X/Y axis, while its natural frequencies in X/Y axis can be increased by two to three times at the expense of decreased stroke, i.e., elastic range. In addition, real-time dynamic-tuning experiments show active vibration cancellation techniques can be implemented on the nanopositioner and effectively eliminate the unwanted dynamics and improve the overall dynamic performance. Lastly, we performed nano-scratching experiments using an 18 tip AFM array to fabricate optical grating patterns on gold coated silicon substrates of $5 \times 1\,\text{mm}^2$ to demonstrate the practicality of the new method. The experiment confirmed good parallelism had been achieved during the experiments, where the scratched gold lines have a consistent depth of ~160 nm.

1. Introduction

Nanomanufacturing is a process to create nanoscale structures, devices and systems (Chryssolouris et al., 2004) that encompasses various technologies, including focused ion beam lithography (FIBL) (Melngailis, 1987), electrohydrodynamic (EHD) jet printing (Park et al., 2007), and two-photon polymerization (TPP) (Cumpston et al., 1999). Tip-based nanofabrication (TBN) is an important and versatile nanomanufacturing technology that utilizes microscale cantilevers with attached nanoscale tips to realize nanofabrication (Tseng, 2011); TBN enables a wide range of manufacturing applications, e.g., material removal, modification, deposition, manipulation etc. (Tseng, 2011), and therein lies its potential to provide pattern flexibility for fast prototyping (Malshe et al., 2010). However, comparing with mask- or template-based nanomanufacturing methods such as photolithography, nanoimprint lithography (NIL) and microcontact printing (MCP), which provide large-area modification and high throughput (Huo et al., 2008), all TBN techniques share a low throughput issue inherited from the serial nature of tip movement (Huo et al., 2008). To circumvent such restriction, two methods are generally applied to improve the TBN throughput (Tseng et al., 2008): operating multiple tips in parallel (Vettiger et al., 2002; Salaita et al., 2006), and increasing the tip operation speed/frequency (Clayton et al., 2009; Kodera et al., 2006). In other words, multi-axis nanopositioners with enhanced speed and precision is the key to ensure successful industrial application of TBN (Bloschock et al., 2011).

Nanopositioners can move objects of different sizes with nanometer level precision. They are important as they set the limits on our ability to measure, manipulate, and manufacture physical systems. As traditional mechanical linkages are susceptible to backlash and wear between joint members, compliant mechanisms, i.e., flexures, are often used to fulfill the strict repeatability and precision requirements (Howell, 2001). However, compliant mechanisms demand a larger device envelope in comparison to the motion they can generate, causing inevitable trade-offs between the natural frequency and range.

To realize large-area parallel nanomanufacturing, e.g., generating nano-patterns on a $1 \times 1\,\text{cm}^2$ substrate, the nanopositioner must meet the following requirements: (1) five degrees of free-

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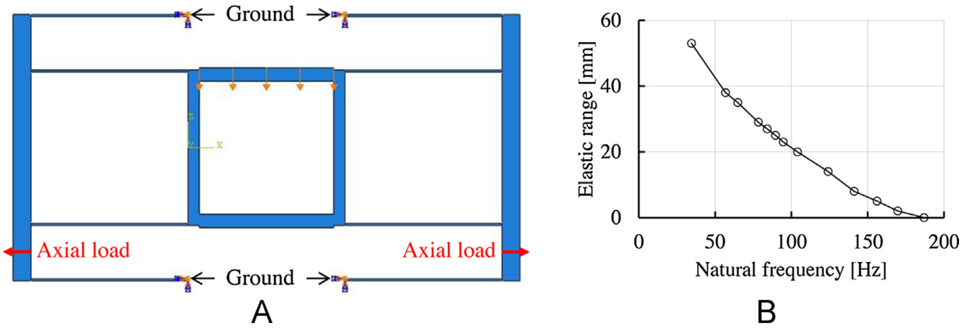

Fig. 1. Simulated results of a symmetric DP flexure using Abaqus 6.12. (A) CAD model with load and boundary conditions; (B) the relationship between the range and frequency of the DP flexure.

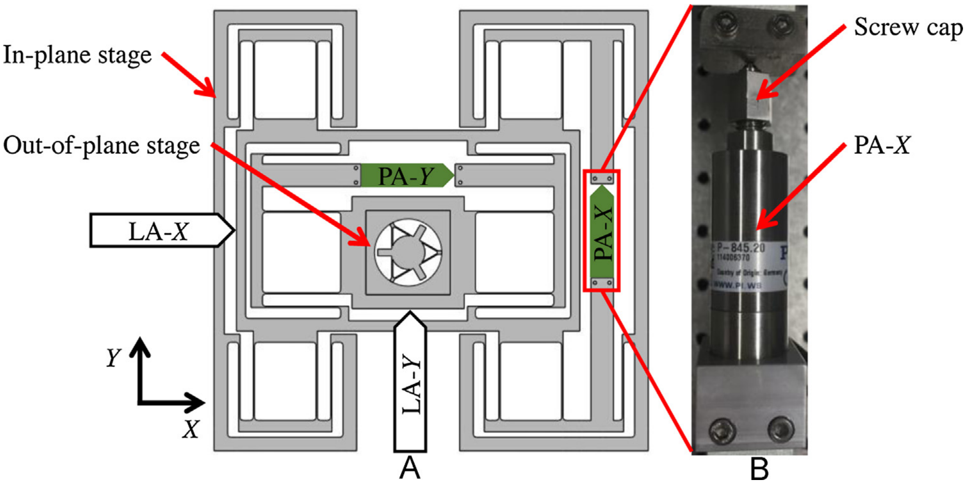

Fig. 2. (A) Layout of the nanopositioner: the green arrows, i.e., PA-*X* and PA-*Y*, indicate the piezoelectric actuators (PI P-845.20) for stiffness-tuning and the white arrows, i.e., LA-*X* and LA-*Y*, indicate the linear actuators (PI M-230.10S) for in-plane actuation. (B) Mechanical installation of the actuator for stiffness-tuning. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dom (DOF), i.e., X, Y, θ_X, θ_Y, and Z, where X and Y axes are for in-plane nanomanufacturing, θ_X, θ_Y,and Z axes are for aligning and positioning the tip array with the substrate; (2) nanometer level repeatability and submicron level precision for position control in all five axes; (3) a range of ±5 mm/±5 mm in the X/Y axis for large-area nanomanufacturing and a range of ±40 μm/±2 mrad/±1.5 mrad in the $Z/\theta_X/\theta_Y$ axis respectively; and (4) dynamic-tuning capability that allows the nanopositioner to travel a long distance to locate and manufacture locally at high speed. Among these requirements, the dynamic-tuning capability is of particular importance as it alleviates the side-effect of low natural frequency induced by a large-stroke flexure-based nanopositioner.

2. Dynamic-tuning for flexure-based nanopositioners

Although the dynamic performance of a flexural mechanism is determined by its natural frequency, it is often compromised by the required stroke of the mechanism. In other words, high natural frequency can only be achieved at the expense of reduced stroke. To be more specific, a high-bandwidth flexure-guided nanopositioner is limited to a relatively small travel range (Yong et al., 2012), while a large-displacement flexure-based nanopositioner has low natural frequencies. For example, a millimeter-ranged flexure-based nanopositioner typically has a resonant frequency less than 100 Hz (Kim et al., 2012). In this paper, we aim to develop a dynamic-tunable flexure-based nanopositioner that allows trade-offs between speed (natural frequency) and range (stroke)—a concept inspired by compliant actuators used in humanoid robots (Vanderborght et al., 2013).

The dynamic-tuning effect is achieved by exploiting the “stress-stiffening effect”, i.e., the increased stiffness of a beam when experiencing tensile loads in the axial direction (Timoshenko, 1947). The natural frequency of a simply supported beam with an axial force N can be described by Eq. (1), where ω is the natural frequency; l, A, I, E, ρ are the length, cross-sectional area, area moment of inertia, Young’s modulus and density of the beam, respectively (Timoshenko, 1947). For example, the natural frequency of a simply-supported rectangular-section titanium beam ($E = 1.048 \times 10^{11}$ Pa, $\rho = 4428.78$ kg/m^3, 70 mm long, 10 mm wide, and 1 mm thick) can be shifted from 450 Hz to 1164 Hz when a 1000 N uniform axial tensile force is applied to one end of the beam. Note that compression load is not used as it may cause buckling and instability.

$$\omega = \left(\frac{\pi}{l}\right)^2 \sqrt{\frac{EI}{\rho A}} \sqrt{1 + \frac{Nl^2}{\pi^2 EI}} \quad (1)$$

To extend the frequency tuning concept from a beam to a flexural mechanism, Fig. 1 presents the simulated results of a symmetric double parallelogram (DP) mechanism where its yield stress is reached by increasing the axial loads. Fig. 1A shows the computer-aided design (CAD) model. The material used in the finite element analysis (FEA) simulation is titanium. Fig. 1B shows that dynamic-tuning enables trade-offs between the natural frequency and the elastic range of the DP mechanism.