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A new preload mechanism for a high-speed piezoelectric stack nanopositioner

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ABSTRACT

Piezoelectric stack actuators are the actuator of choice for many ultra-high precision systems owning to its fast responses and high pushing force capabilities. These actuators are constructed by bonding multiple piezoelectric layers together. An inevitable drawback of these actuators is that there are highly intolerant to tensile and shear forces. During high-speed operations, inertial forces due to effective mass of the system cause the actuators to experience excessive tensile forces. To avoid damage to the actuators, preload must be applied to compensate for these forces. In many nanopositioning systems, flexures are used to provide preload to the piezoelectric stack actuators. However, for high-speed systems with stiff flexures, displacing the flexures and sliding the actuators in place to preload them is a difficult task. One may reduce the stiffness of the flexures to make the preload process more feasible; however, this reduces the mechanical bandwidth of the system. This paper presents a novel preload mechanism that tackles the limitations mentioned above. The preload stage, which is connected in parallel mechanically to a high-speed vertical nanopositioner, allows the piezoelectric stack actuator to be installed and preloaded easily without significantly trading of the stiffness and speed of the nanopositioning system. The proposed vertical nanopositioner has a travel range of 10.6 μm. Its first resonant mode appears at about 24 kHz along the actuation direction.

1. Introduction

Piezoelectric stack actuators have been used in many high-speed nanopositioners [1–7] and precision systems [8–11] due to their high-bandwidth and large pushing force capabilities. The fundamental component of piezoelectric stack actuator is a thin layer of piezoelectric material sandwiched by two electrodes. All of these piezoelectric layers are poled in the direction of their thickness as illustrated in Fig. 1. The piezoelectric layers are bonded in series mechanically with opposite poling direction to each other. Their electrodes are connected in such a way that the layers are in parallel electrically. When a voltage V is applied to the piezoelectric stack actuator, its estimated total displacement is $\Delta l = nVd_{33}$, where n is the number of piezoelectric layers, and d_{33} is the piezoelectric coefficient. Without load, Δl is roughly around 0.1% to 0.15% of the actuator length [12].

Piezoelectric stack actuator is highly vulnerable to tensile and lateral forces [12]. High inertial force due to effective mass of the nanopositioning system during high-speed operations could potentially damage the actuator [13,14]. A common practice to avoid such damage is to mechanically preload the actuator in the installation to compensate for these forces. A conventional preload mechanism involves a preload screw and block [1,15–17], as illustrated in Fig. 2(a). The screw is used to push the preload block against the piezoelectric stack actuator. Whilst this preload method is simple and effective for low-speed operations, at high-speed the screw and preload block act as a mass-spring system that interferes with the dynamics of the nanopositioning system. Another common way of preloading the actuator is to use a pair of wedges [16–19] as shown in Fig. 2(b). One of the wedges is attached to the actuator. When the other wedge is pushed down, the actuator is pushed forward due to the slope of the wedges. As a result, a preload is applied to the actuator. This preload method may induce lateral forces to the piezoelectric stack actuator which could potentially damage it. Some other preload methods include using permanent magnets [20], a preload bolt [21] and a dual-stack with bidirectional actuation [22].

Flexures have been used in many high-speed nanopositioner designs to simultaneously preload and guide the motion of the piezoelectric actuators [23–25]. To install and preload the actuators in these high-speed systems, forces are applied to elastically deform the flexures in order to make room for the actuators [see Fig. 2(c)]. The piezoelectric stack actuators are gently slided into

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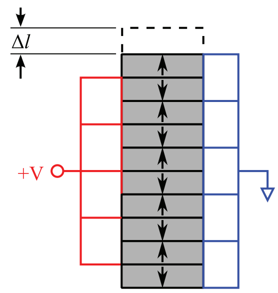

Fig. 1. Piezoelectric stack actuator.

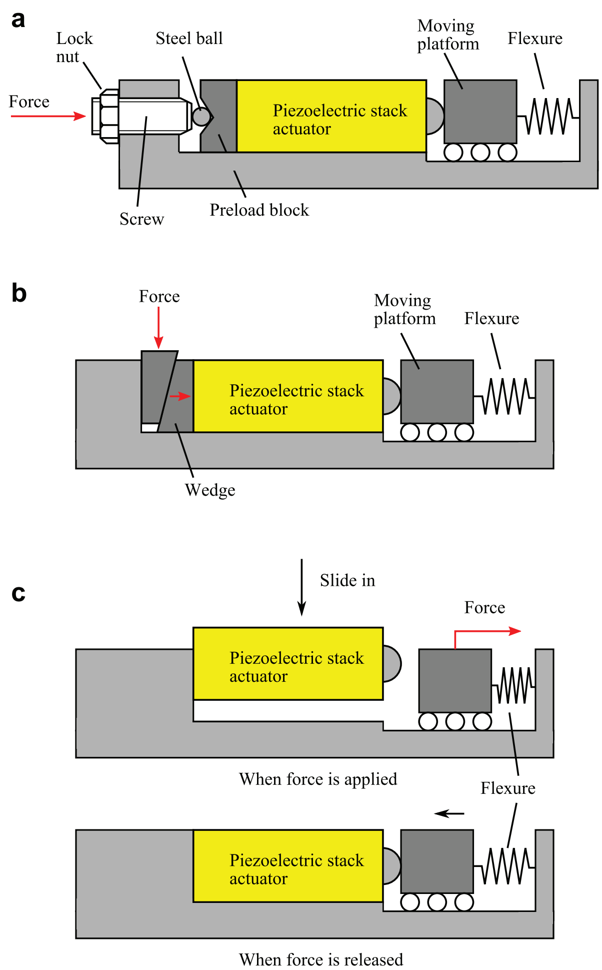

Fig. 2. Common preload methods.

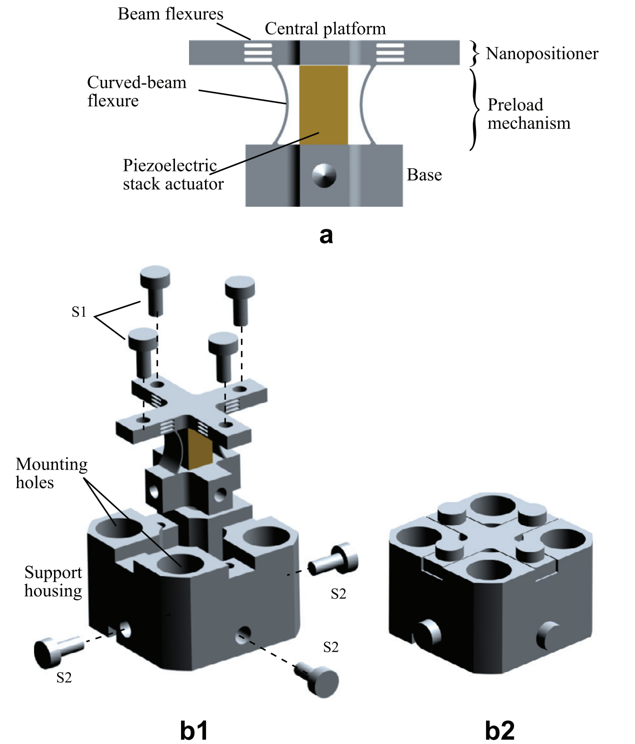

Fig. 3. (a) A high-speed vertical nanopositioner with a novel preload mechanism. (b1) An exploded view showing the nanopositioner and its support housing. (b2) Assembled view of the nanopositioning system.

their designated spaces. The applied forces are then released to restore the flexures to their original position in order to clamp the actuators in place. For high-speed systems, flexures are designed to be stiff (about 10% of the actuator's stiffness) in order to achieve high mechanical bandwidth [1]. Displacing these stiff flexures is a difficult task. For example, to deform a set of flexures with effective stiffness of 10 N/μm [23,24] by 0.1 mm, a large pulling force of 1000 N is required. It is impractical to hang a 100 kg dead weight on the flexures to deform them. A carefully designed pulley system or a high-force preloading tool may be needed for this challenging task. Another approach to make the preload procedure more feasible is to reduce the stiffness of the flexures, however, this also reduces the resonances and speed of the nanopositioning system.

This paper proposes a novel preload mechanism which deals with the aforementioned challenges in high-speed nanopositioning systems. The proposed nanopositioner design is a single-axis high-speed vertical stage. Vertical nanopositioning stages have many applications in the area of precision positioning, such as in the field of atomic force microscopy [5], alignment of optics [12,26], and objective scanners [27,28]. The preload stage, which is connected in parallel mechanically to a high-speed nanopositioner, allows for the ease of preloading and installation of the piezoelectric stack actuator without significantly trading-off the stiffness of the nanopositioning system.

The remainder of the paper is organized as follows. Section 2 describes the design configuration of the proposed nanopositioner. Stiffness and stress analysis of the nanopositioner is presented. Range and resonance frequency of the system are also estimated and presented in this section. Section 4 presents the experimental results of the nanopositioner. Conclusions are drawn in Section 5.

2. Design analysis of the nanopositioner

A high-speed vertical nanopositioner with a novel preload mechanism is shown in Fig. 3. The nanopositioning stage consists of four sets of beam-flexures to guide the motion of the central platform, and to provide the requisite stiffness to the structure. Mechanically in parallel is the preload mechanism that consists of two curved-beams. These curved-beams connect the central platform to the base of the device. A piezoelectric stack actuator is located between the platform and base. When a voltage is applied to the actuator, it displaces vertically, which in turns, elastically deforms the flexures to move the central platform vertically.