IN-PLANE FORCE SENSING OF MICROELECTROMECHANICAL SYSTEMS

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ABSTRACT
With the advancement of miniaturization, many micromechanisms are fabricated by Microelectromechanical System (MEMS) processes. Most characterization methods of micromechanisms rely on optical or tactile techniques. Due to increasing complexity and decreasing size of microsystems, it becomes more challenging to measure the force-displacement characteristics of micromechanisms. Commercial atomic force microscopes and nano indenters have been utilized for precise force sensing of micromechanisms. These commercial equipments are expensive and economical characterization methods are required for design and evaluation of micromechanisms in laboratories and production. Therefore, a device of in-plane force measurement of micromechanisms is developed, which is equipped with translation stages and a miniature load cell. Force-displacement characterization of a constant-force bistable mechanism (CFBM) using the developed device is demonstrated.

Keywords: In-plane force-displacement characterization, Micromechanism.

INTRODUCTION
Atomic force microscopes (AFM) and nano indenters can be used to measure force-versus-displacement (f-δ) curves of MEMS at high resolutions [1,2]. The f-δ curves provide valuable information on MEMS material properties and spring constants of micromechanisms. Implementation of AFM requires delicate scanning, sensing and control systems [1]. Successful force measurements by nano indenters may need protrusions or asperities on top of the micromechanisms for the indenter diamond to catch and drag the specimen on its trajectory [2]. Commercial AFMs and nano indenters are expensive and economical in-plane force characterization methods are needed for design and analysis of micromechanisms in laboratories.

Some researchers have developed various techniques for in-plane force characterization of micromechanisms. Miyamoto et al. [3] measured the f-δ curve of a MEMS spring by means of a servo-controlled balance for force measurement and a photoelectric transducer for displacement measurement. An electrostatic gripping is required for precise gap control between the grip and the specimen. Using their elaborate force-feedback balance, a sub-micro-Newton of force measurement resolution of micromechanisms within a few or few tens of micrometers displacement can be achieved. Beyeler et al. [4] presented a microfabricated 6-axis force-torque sensor based on the measurement of a deflection of the sensing element by several capacitors. Readout electronics are needed to transform the change of capacitance to a change of voltage. A resolution in the range of a single micro-Newton and nano-Newtonmeter can be achieved by their capacitive force sensor. Akanda et al. [5] developed a force sensor by incorporating a cantilever, a probe and a capacitive sensor for force measurement of microstructures with a resolution of 10 nano-Newton. Delicate design and fabrication of the cantilever are necessary for successful implementation of their device.

In this investigation, a device for in-plane force measurement of micromechanisms is developed. A simple mechanism design to drive a probe adhered to a load cell is developed. A micromechanism is fabricated by electroforming and tested by the proposed device. Force resolution on the order of micro-Newton and displacement resolution on the order of micrometers can be obtained. The experimental f-δ curve agrees with that obtained by finite element analyses.

METHODOLOGY

Design
Fig.1 illustrates the design concept of a device for in-plane force measurement of micromechanisms. A Cartesian coordinate system is also shown in the figure. The substrate with specimens for testing is mounted on a rotation stage. The stage can rotate with respect to the z axis. A probe for pushing the micromechanism is attached to a load cell which is fixed to a translation stage. The translation stage has
three translational degree of freedoms in $x$, $y$, and $z$ directions.

![Fig. 1. Concept of a device for in-plane force measurement.](image)

The components of the device are shown in Fig. 2(a). The dimensions of the probe are indicated in Fig. 2(b). In order to facilitate the translation of the probe parallel to the substrate and to maintain contact of the probe tip with the micromechanism, the tip of the probe is machined to have a $135^\circ$ slant angle to the probe axis as shown in Fig. 2(c). The translation stage has a resolution of 10 $\mu$m in $x$, $y$, and $z$ directions. The resolution of the rotation stage is $1/6^\circ$. The load cell (LVS-5GA, Kyowa Electronic Instruments Co., Ltd.) has a rated capacity of 50 micro-Newton (mN). Fig. 3 is a photo of the device. The alignment of the probe axis to the loading axis of micromechanisms is adjusted by the rotation stage and the three-axis translation stage so that the micromechanism does not twist during loading.

![Fig. 2. (a) Components of the device. (b) Dimensions of the probe. (c) A close-up view near the tip of the probe.](image)

In order to demonstrate the feasibility of the proposed device, a CFBM with the characteristics of nearly constant output force over a range of displacement is fabricated. A schematic of a CFBM is shown in Fig. 4. The mechanism is a compliant chevron-type mechanism consisting of a shuttle mass, a guide beam, curved beams and lateral beams. Fig. 5(a) shows a typical $f$-$\delta$ curve of the CFBM. Fig. 4(b-e) illustrates a four-step operation of the mechanism. First, a force $F$ is applied to the mechanism through the shuttle mass (see Fig. 5(b)). When the deflection of the shuttle mass is within the interval of $\delta = b$ to $\delta = c$, the mechanism generates a nearly constant output force over this range of displacement, hence defined as operational range, $D$ (see Fig. 5(a)). The maximum output force $f_d$ occurs at the displacement $\delta = d$ (see Fig. 5(d)). $f_e$ is the minimum output force of the CFBM and has a negative value (see Fig. 5(a)). When the force applied to the mechanism $F$ is greater than $f_d$, the mechanism moves towards its second stable position $g$ (see Fig. 5(e)), where the output force of the CFBM is zero.

![Fig. 3. Photo of the device.](image)

![Fig. 4. A schematic of a CFBM.](image)

![Fig. 5. (a) A typical force versus displacement curve of the CFBM and the corresponding positions at displacement $a$ (b), displacement $c$ (c), displacement $d$ (d), and displacement $g$ (e).](image)
Experiments

Fig. 6 is a photo of a CFBM fabricated by an electroforming process. The CFBM is tested using the proposed device as shown in Fig. 3. Fig. 7(a-d) show sequences of snapshots from experiments. As shown in Fig. 7(a), when the probe touches the edge surface of the shuttle mass, a force is applied to the CFBM. When the magnitude of the force is increased, the shuttle mass moves downward (see Fig. 7(b)). As the force reaches a certain maximum value, the probe tip loses contact with the edge surface of the shuttle mass, and the mechanism snaps into its second stable equilibrium position (see Fig. 7(c)). When the probe tip is translated to touch the edge surface of the shuttle mass, the shuttle mass is pushed further downward (see Fig. 7(d)).

The experimental $f$-$\delta$ curve is shown in Fig. 8. The $f$-$\delta$ curve of the mechanism bases on finite element computations is also shown in the figure. A nearly constant force is measured using the proposed device. The value of the nearly-constant force output of the experiments is close to that based on the finite element analyses.

RESULT

With the proposed device, it is possible to measure the in-plane force-displacement curves of micromechanisms. The sensing of the force output is realized by a probe connected to a load cell. To facilitate the contact of the probe to the micromechanism, a flat surface area of the micromechanisms is required. The in-plane force and displacement measurement resolutions achieved by the device are on the order of micro-Newton and micrometer, respectively, which may be precise enough for force characterization of MEMS in laboratories.

REFERENCES