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An active MEMS probe for fine position and force measurements

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ABSTRACT

This paper deals with the development and calibration of a single degree-of-freedom probe that is capable of regulating an input position and measuring force or applying a constant input force and measuring deflection. Such a probe is useful in making sensitive measurements on thin films, nano- and micro-structures, and fluids. The probe is actuated by an electrostatic comb drive with an integrated capacitive sensor. COTS electronics and a capacitance-to-voltage IC are used to develop a closed-loop controller for the system, capable of regulating position over a range of about 40 μm to within a 5 nm resolution and controlling forces up to 300 μN with a resolution of 25 nN. The design and fabrication of the probe are discussed. The calibration of the device is performed using multiple methods to cross check each other. The use of the probe is demonstrated in the measurement of surface tension and probing the response of a soft polymer to small forces.

1. Introduction

The accurate determination of small forces has far-reaching applications in micro- and nanoscience and technology. Such measurement are required in assessing the strength and mechanical properties of nanostructures like carbon nanotubes (CNTs) and nanowires, thin films of graphene and other monolayers, as well as their behavior when subjected to forces (Van der Waal, electrostatic, optical pressure, etc.) when interacting with other structures or the environment; measurement of fluid properties such as surface tension and viscosity, especially those of bio-fluids where the available quantities are very small; in cellular mechanics to mechanically characterize the behavior of cytoskeletal structures and the extracellular matrix, and the role these behaviors play in mechano-transduction and other cellular processes; in single molecule studies where one might be interested in individual bond strengths; and other such fundamental studies. In all these examples the ability to apply and measure small forces and motions plays a defining role. A number of instruments ranging from microbalances to nano-indenters to atomic force microscopes (AFMs) have been demonstrated to be useful in such measurements. Each instrument however comes with different advantages and disadvantages associated with measurement range; resolving limits; dynamic range; repeatability and drift; calibration to an acceptable standard; instrument form factor and interaction with the specimen; operational modes, e.g., ability measure force (position) while controlling position (force); and active positioning capabilities. For example, AFMs provide for very high resolution, but reduced measurement range and do not have the ability to actively control force or position. Similarly, a nano-indentation system has reduced force resolving capability, but can control the force it applies and measure displacement. In short, there is growing need for a flexible and highly tunable platform for applying and measuring small forces.

A micro-electro-mechanical systems (MEMS) platform offers the possibility of an affordable, small form factor, high-bandwidth force probe that can achieve different sensitivities by small dimensional modifications (e.g., changing the dimension of a leaf strip) and some end-effector redesigns to suit particular applications. Because of these features and the previously described diversity of applications, research into MEMS-scale devices for force measurement is actively pursued by a number of research groups. Kenny et al. [1] provides an instructive starting point for MEMS-based force measuring devices, analyzing different measurement approaches such as optical, piezoresistive, tunneling current, magnetomotive and capacitive sensing for their fundamental limits and confounding effects. Gnerlich et al. [2] have developed a 4 mm × 4 mm piezoresistive MEMS force sensor with a combined electrical and mechanical sensing element for the study of cell biomechanics. Fabricated using DRIE on doped SOI wafer, the device is directly submerged in call medium and measured forces from 5 nN to 38 nN while compressing a cell. Rajagopalan et al. [3,4] developed a MEMS force sensor consisting of flexible beams

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attached to a rigid probe for the study of forces generated by cells in many cellular processes. The force sensor is demonstrated to produce measurements with resolution of 50–500 pN with a force range of 100 nN to 1 μN in measuring mechanical response of Drosophila axons. Beyeler et al. [5,6] developed a 6-axis force-torque sensor based on the measurement of mechanical deflection of sensing elements by a number of variable capacitors. It measures forces up to 700 μN and torques up to 750 nN-m with noise level of 0.5 μN and 0.5 nN-m for force and torque, respectively. Calibration of the sensor is performed by commercial single-axis reference force sensor (FemtoTools FT-S270). Mukundan and Pruitt [7] have also used electrostatic comb-drives to study the stiffness of cells cultured on suspended structures. The sensor is operated in the frequency range of 1–10 MHz and the behavior of transition frequency, depending on electrostatic force, is characterized in media of different ionic strengths. Zhang and Dong [8] designed and fabricated a SOI-MEMS-based active microprobe for cellular force sensing application. The sensor has a single comb drive for actuation and two sets of combs for capacitive sensing. It is focused on sensing cellular force from a few nN to μN with a sensitivity of 6 fF/μm. As previously mentioned, AFMs are often employed in force measurements by using cantilevers with pre-calibrated stiffness. Unlike MEMS devices which typically record forces in the direction parallel to probe axis, AFM-based devices [9–11] record forces in the direction perpendicular to the cantilever. AFM-based devices can produce high resolution but have limited range of motion and therefore the force range is typically low. Using the cantilever as a tuning fork in an AFM's dynamic force measurement mode, Polesel-Maris et al. [11] have demonstrated the measurement of force signatures during protein unfolding. Using contact mode AFM experiments, Wang et al. measured forces in similar experiments to be in 870 ± 390 pN range. A quick analysis of the literature reported above suggests that for a majority of the MEMS devices, as well as the AFM techniques that directly measure force, the probing is passive. In cases where dynamic modes are used, phase or amplitude modulation are used to indirectly measure forces. Active, closed-loop measurement of forces, while regulating position or vice versa (regulating force while measuring deflection), has seldom been attempted.

A second important issue in measuring small forces is the traceable calibration of the device. The units for force include the basic units of time, mass, and length, making the direct calibration of force difficult. Force calibrations are therefore done indirectly, by comparison with other known forces. For example, gravitational force on a known, calibrated mass can be used to calibrate forces. However, the smallest NIST-calibrated mass available is 0.5 mg [12] which corresponds to gravitational force 5 μN. Further, the approach of using a smaller mass artifact for measuring smaller forces does not scale because of the rapid growth of uncertainty. For traceable measurements of forces below the 5 mN values, NIST has developed an electrostatic force balance that links small sources in the mN–nN range to stable electrical units like voltage and capacitance [12,13]. Within the context of the use of AFMs for scanning force microscopy [14] and nanoindentation instruments that use cantilevers, the calibration problem has received a good bit of attention. Several techniques have been proposed to calibrate AFM cantilever spring constants. These include the added-mass technique [15–19] in which resonance frequency shifts are observed under known mass perturbations, the inference of stiffness of a cantilever from its thermal noise spectrum [20], by loading the cantilever with a known force [21,22], or by inference from its dimensions and its resonant frequency and quality factor in a fluid [21]. Traceable calibration approaches have received much less attention in the context of non-cantilever MEMS force probes.

In this paper we develop an active MEMS-scale probe with both actuation and sensing integrated into the platform. The system

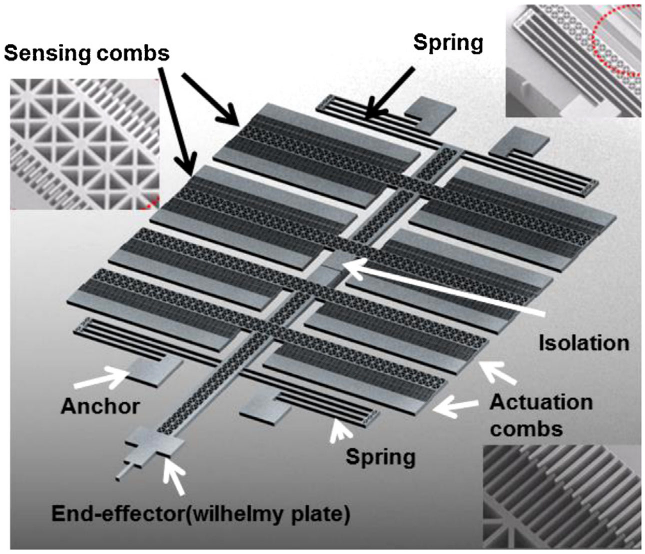

Fig. 1. Solid model of the probe with key parts identified. SEMs of important features of the stage provide details.

is operated under closed-loop control so that the end-effector's position can be regulated while measuring force, or the force exerted by the probe can be can be regulated while monitoring position. This creates a very flexible platform for making direct force measurements or for measuring the mechanical response (displacement) of small structures under the action of a known applied force. In Section 2 of this paper, we discuss the design and fabrication of an electrostatically actuated probe with capacitive sensing of force. Section 3 addresses the problem of calibration of the probe. As we have previously discussed, for small forces in the nN–μN range, traceable calibration of the probe can be quite difficult. Here, we use multiple approaches to estimate both the stiffness of the probe and the force constant of the electrostatic actuator. The estimates produced agree to within a 2–5% uncertainty band. Section 4 discusses the design and performance obtained under closed-loop servo control. In Section 5, the application of the probe is demonstrated in making measurements of surface tension and applying small forces on a soft polymeric substrate. Section 6 closes with conclusions and future work.

2. Design and fabrication

An SOI-wafer was chosen as the substrate for fabrication because of the simplicity in fabrication and ease of release offered by such substrates. Fig. 1 shows a solid model of the probe. Fabricated on an SOI wafer, it consists of a central movable stem that holds the end-effector (in this figure, it is a series of three stepped plates to be used for mico-Wilhelmy [23] measurements). The stem is suspended on a pair of folded leaf springs. Electrostatic comb drives are chosen for actuation, while a second set of capacitance combs sense displacement. This choice is based on both, the sensitivity and resolution ranges of these technologies, and the ease of fabrication with conventional processes. The actuating and sensing combs are located between the leaf springs for maximum stability. The moving parts of the actuating and sensing combs are carried by the stem. A channel in the device layer electrically isolates the sensitive low-voltage sensing circuit from the high-voltage actuation circuit on the moving stem. However, they remain mechanically connected by a lap joint, where the overlapping member is created in the handle layer by retarding part of the handle layer etching performed to release the device.