A.3. Piezoresistive-based Microcantilever Sensors with Application to Nanoscale Force Detection

When microcantilevers were used as the force sensor in AFM, researchers found out about their tremendous sensitivity to different environmental factors such as acoustic noise, light, temperature, humidity and ambient pressure. Due to the simplicity and availability, the AFM instrumentation has attracted widespread attention during the last decade. Increasing the number of researches in different disciplines such as biological, material science, imaging and sensing indicate the importance of the microcantilever based sensor and actuators.

Due to the recent advances in manufacturing of the microcantilevers with different shapes and material properties and embedded actuation and sensing capabilities, sensing based on the bending of microcantilever beams are known as the simple, inexpensive and accurate way when compared to conventional sensing methods. A microcantilever model has been suggested in the literature to predict the change of spring constant caused by surface stress, DNA hybridization and/or receptor-ligand binding. Same studies based on the biochemical–mechanical transduction have recently been reported in adsorption of low-density lipoprotein, antigen–antibody binding, and an artificial nose. In all the above approaches, the surface stress is mainly measured by acquiring the microcantilever deflection utilizing an optical lever technique such as laser microscopy; however, alignment and calibration of the optical element for different testing species are not trivial, the optical lever technique is costly and even may fail when operating in non-transparent liquid.

Microcantilever’s deflection and surface stress measurement via piezoresistive layer has been recently proposed. Piezoresistive cantilevers are usually used in force microscopy applications where difficulties in laser alignment make optical detection inconvenient. Some of the piezoresistive-based sensing applications are atomic data storage systems, cantilever arrays, high vacuum AFM measurements and portable cantilever-based sensors. Even though numerous studies have recently focused on piezoresistive microcantilever sensors, almost in all of them, the piezoresistive microcantilever is replaced by a simple lumped-parameters model. Due to the extreme precision of the piezoresistive microcantilever sensors, which is in the range of the nano-Newton, utilizing a more precise modeling approach is critical. Here, a distributed-parameters modeling approach is proposed and developed to obtain the most accurate model of the piezoresistive microcantilever.

Microcantilever-based sensors and actuators have recently attracted wide spread attention due to tremendous applications in biological and material science technologies. Nanomanipulation, defining materials properties, fabricating electronic chipsets, testing of microelectronics circuits, assembly of MEMS, teleoperated surgeries, micro-injection and manipulation of chromosomes and genes serve as demonstrable examples of microcantilever applications. More specially, Fig. 16 depicts a 3DOF nanorobotic manipulator, namely MM3A, which is utilized for nanomanipulation, identification, sensing and imaging purposes [13-23]. The piezoresistive microcantilever which can be appended to the nanomanipulator’s tip (see Fig. 17-a), combined with its base motion and alignment provided by the nanomanipulator, can be utilized in variety of applications, such as force sensing, non-contact AFM imaging and nanomanipulation with nanoscale resolution requirement.

In the previous publications of the authors, the problem of modeling and control of MM3A nanomanipulator has been addressed and a novel control framework was proposed to provide the most accurate movement of the nanomanipulator’s tip at nano-scale. In order to employ a combined task of nanomanipulation and piezoresistive-based sensing, there is a need to precisely model the piezoresistive microcantilever to arrive at a relationship between piezoresistive layer output and base motion and tip force of the microcantilever.
Due to the interaction force between nanomanipulator’s tip and nanoparticle, the piezoresistive microcantilever bends and because of the longitudinal deflection of the beam, the electrical resistance of the piezoresistive layer on the microcantilever changes (see Fig. 17). This change in piezoresistive layer’s electrical resistance can be converted to the electrical voltage signal by utilizing a simple electrical circuit.

Here, the piezoresistive microcantilever is modeled as a clamped-free beam with a boundary force and a mass on its tip and base motion consideration. Utilizing an energy method and the Extended Hamilton
approach and considering the coupling between piezoresistive layer and the beam, dynamic equations of the motion of distributed-parameters system are obtained. As shown next, by utilizing the distributed-parameters model rather than lumped-parameters approach and by predicting the exact motion of each point on the microcantilever, the precision of the piezoresistive microcantilever’s model is significantly enhanced.

A set of experimental tests is utilized here to demonstrate the accuracy and effectiveness of the proposed modeling approach and simulation. The experimental setup consists of Polytec MSA-400 Micro System Analyzer, Physik Instrumente (PI) P-753.11c PZT-driven nanostage, PI E-500 Modular Piezo Control System, PI M-126.DG translation microstager, PI C-809.40 4-channel servo-amplifier-Motion I/O interface, dSPACE DS1104 controller board, Pulnix TM-1400 camera with 50x Mitutoyo lens, Kleindieck FMS-EM force measurement system, and Seiko Instruments Institute PRC-400 self-sensing microcantilever (see Fig. 18).

![Fig. 18 The experimental setup at SSNEMS Laboratory.](image)

P-753.11c PZT-driven nanostager combined with PI E-500 Modular Piezo Control System are utilized here to move the piezoresistive microcantilever’s base with sub-nanometer precision (see Fig. 19). P-753.11c PZT-driven nanostager, with unique design, frictionless precision flexure guiding system, 0.05 nm resolution, direct metrology with capacitive sensors for highest precision and ultra-fast response combined with the E-500 Modular Piezo Control System provide the possibility to move the piezoresistive microcantilever’s base with sub-nanometer precision and having the ultra precise position feedback at the same time. Extensive theoretical and experimental modeling has been performed by the research team to model and precisely control the positioning of such nanostager.

M-126.DG translation microstager combined with PI C-809.40 4-channel servo-amplifier-Motion I/O interface are utilized here to move the piezoresistive microcantilever’s base with sub-micrometer precision (see Fig. 20). PI M-126.DG translation microstager with 25 mm travel range, novel ActiveDrive concept, crossed roller bearings and less than 0.1 µm resolution combined with 4-channel servo-amplifier is a complete solution to move the piezoresistive microcantilever’s base with sub-micrometer resolution in a wide range.
The FMS-EM force measurement system by Kleindiek combined with the PRC-400 self-sensing microcantilever by Seiko Instruments Institute are utilized here as the piezoresistive microcantilever with its Wheatstone bridge and amplifier (see Figs. 17 and 21). The FMS-EM module with 80 μN maximum tip force and $3.1 \times 10^3$ mV/nm sensitivity is a perfect solution for variety of force sensing applications, namely, contact and non-contact force microscopy, nanoindentation, tensile measurement and MEMS analysis.
The experimental procedure consists of applying different static forces to the piezoresistive microcantilever’s tip and monitoring the output voltage of the piezoresistive layer. Hence, there is a need to be able to move the microcantilever in the Cartesian space in the macro-range with nano-scale precision. For this, a combination of nanostage, microstage and a manual stage is utilized for such purpose (see Fig. 22).

![Combination of nanostage, microstage and a manual stage to move the cantilever at SSNEMS Laboratory.](image)

**Fig. 22** Combination of nanostage, microstage and a manual stage to move the cantilever at SSNEMS Laboratory.

A holder is designed and provided to mount the PRC-400 self-sensing microcantilever to the nanostage. Utilizing the FMS-EM force measurement system, the microcantilever’s deflection is converted to the output voltage which is fed back to the DS1104 dSPACE. This whole process is running under the Pulnix TM-1400 camera and MSA-400 to provide the image and position feedback of the microcantilever.

In order to calibrate and verify the derived closed-form solution, there is a need to apply predefined forces to the piezoresistive cantilever’s tip and monitor the output voltage and then compare it with the simulation results. Here, a calibration weight is employed for such a purpose (see Fig. 23).

![Calibration weight utilized to apply the predefined force to the microcantilever at SSNEMS Laboratory.](image)

**Fig. 23** Calibration weight utilized to apply the predefined force to the microcantilever at SSNEMS Laboratory [15].
As seen in Fig. 23, the calibration weight is a see-saw mechanism with a predefined weight on one end (1.67 mg = 16.4 µN). Fig. 24 illustrates the principle by which a predefined force applies to the microcantilever’s tip.

As seen in Fig. 24, by depressing one side of the see-saw until the 16.4 µN ball is suspended, a constant force is exerted to the microcantilever’s tip. Accordingly, force \( f \) which is exerted on the microcantilever’s tip, can be defined as:

\[
f = \frac{16.4 \times l_1}{l_2 - x}
\]

where \( l_1 \), \( l_2 \) and \( x \) are measurable and by placing the microcantilever in different distances (\( x \)), different predefined static forces can be applied to the microcantilever’s tip.

Fig. 25 depicts the overall experimental procedure (images taken by MSA-400). As seen in Fig. 25, the free end of the see-saw is placed under the MSA-400 micro system analyzer, then the piezoresistive microcantilever is approached to the see-saw’s lever and pushed it downward until the calibration weight gets suspended, the output voltage of the piezoresistive layer at this moment is read and registered.

For each value of \( x \), the experiment is repeated for three times and totally thirteen different values of \( x \) is tested. The simulation results for the lumped-parameters modeling and distributed-parameters models with different number of modes and experimental results are depicted in Fig. 26. The experimental results are also depicted in this figure. Three experimental results for each applied force to the microcantilever are plotted and the best line fitted to these experimental results is sketched. As seen in Fig. 26, the output voltage of the piezoresistive layer almost linearly varies with changing the force on the microcantilever’s tip. In Fig. 27, the best line fitted to the experimental results is defined and plotted. This line can be expressed by following equation:

\[
V_o (\text{volt}) = 0.394 \times f \ (\mu N)
\]
Fig. 25 Experimental procedure at SSNEMS, (a) PRC-400 microcantilever, (b) The calibration see-saw, (c), (d) and (e) Exerting different forces to the microcantilever’s tip [15].

Fig. 26 Experimental and simulation results for the lumped-parameters modeling (LPM) and distributed-parameters modeling for $i$ modes (DPM-$i$) of the piezoresistive microcantilever, points for the 1$^{st}$ experiment (*), 2$^{nd}$ experiment (+), and 3$^{rd}$ experiment (o), [15].
As seen in Fig. 26, by employing more than two modes, the distributed-parameters closed-form modeling can precisely predict the piezoresistive microcantilever’s output voltage due to an applied tip force. However, utilizing the commonly used lumped-parameters model, results in a 20% error in the predicted output voltage.

**Fig. 27** Experimental results points for the 1st experiment (*), 2nd experiment (+) and 3rd experiment (o) and the best fitted line [15].
This subtask has resulted in the following publications during this report period.


