doi:10.1017/S1431927622003956
Microsc. Microanal. 28 (Suppl 1), 2022

Cantilevered Plates for Micrometrology

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Cantilevered sensors are ubiquitous in micro-metrological applications, for instance in atomic force microscopy and analyte detection. Typically, thin, narrow cantilevered beams are used. In this work, we consider a wide, cantilevered plate for micrometrology. We focus specifically on contact resonance atomic force microscopy (CR-AFM) methods, in which AFM cantilevers are resonated while in the linear net-repulsive force region of the tip-sample contact. CR-AFM has been used to perform highly accurate, quantitative, nanomechanical measurements and has been successfully used to measure nanoscale elastic properties [1], viscoelastic properties [2], and subsurface topography [3]. In this work, we show that using a plate-like AFM cantilever geometry creates several transformative advantages over the current methodology, which utilizes a thin-beam geometry.

By re-formulating CR-AFM using Kirchhoff-Love plate theory, we show that using plate-like geometries increases the modal density of the system, thereby increasing the amount of experimental information available within a given measurement frequency bandwidth. Additionally, an array of eigenmodes, beyond the classical transverse bending modes of a Bernoulli-Euler beam, are naturally included in the method, such as plate-like and torsional modes. These additional modes can be readily used to extract sample material properties and do not require additional modeling efforts. Further, we present a rigorous identification method, in the form a generalized eigenvalue problem, that will be easily implemented by AFM researchers via off-the-shelf numerical routines. The solution method is designed to incorporate an arbitrary amount of measured contact resonance frequencies. Additionally, we present an analysis to determine the optimal tip placement location and plate aspect ratio to inform the design of such devices.

Next, we extend our method to incorporate visco-elastic samples. The purely elastic model is updated to included damping. The Rayleigh-Ritz solution method creates a new "unconventional" eigenvalue problem which must be solved. Results are verified via a numerical experiment and discussed.

Finally, we consider the addition of curvature to our wide plate sensor. A finite element model is developed and virtual contact resonance experiments are performed. We find that, with the addition of curvature, the sensor stiffness of the component eigenmodes can be arbitrarily tuned, which is a very beneficial property for AFM contact imaging modes that rely on resonance amplification, for example: CR-AFM, scanning Joule microscopy, piezoforce microscopy, and electrochemical strain microscopy. Additionally, we find that the evolution of the eigenmodes of the system, as a function of system curvature, behave in complicated ways. We observe eigenvalue crossing and veering phenomena and offer methods to mitigate these effects on the measurement process. We also discuss how varying the curvature of the plate-like sensor can be used in micro-metrological applications outside of CR-AFM.

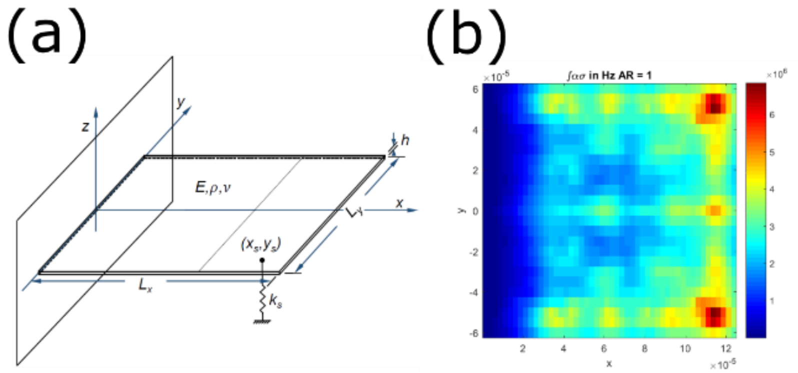

Figure 1: (a) Cantilevered plate proposed for use in CR-AFM. (b) Frequency sensitivity to stiffness changes for varying tip locations. The plate is fixed on the left side and free on all other sides. Tip locations in the vicinity of the corners of the plate optimize sensitivity across the measurement bandwidth.

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https://doi.org/10.1017/S1431927622003956 Published online by Cambridge University Press