An Effective Stiffness Approximation for Atomic-Force-Microscope Cantilevers

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Abstract

An atomic force microscope can acquire both topographic and materials-related data, but with cantilevers of different stiffnesses. Unfortunately, changing cantilevers causes the cantilever tip's position over the sample to be lost. By oscillating a single cantilever at an overtone, however, it may be possible to emulate a cantilever of higher stiffness. Using an AFM simulator, I.C. Adams, tests were performed to determine the veracity of this theory. These tests demonstrated that the method has merit, but further experimentation is necessary.

Intermittent-Contact Mode

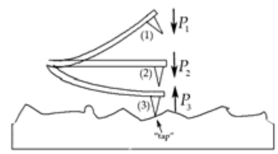

Fig. 1 - Intermittent-contact mode

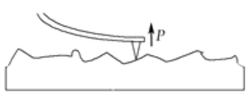

Fig. 2 - Contact mode

This project revolves around intermittent-contact mode, a form of data-acquisition in which the cantilever occasionally taps the sample. This strong oscillation helps keep the cantilever from getting stuck or twisting due to contact with the sample, which may be a problem in other modes, such as contact mode.

A diagram of intermittent-contact mode versus contact mode are found in Figures 1 and 2.

Approach Curves

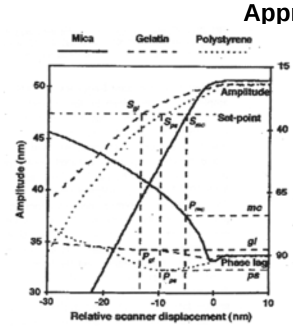

Fig. 3 – An approach curve

An approach curve, or "force curve," is a way of expressing of the motion of the cantilever as the scanner approaches the sample. In Figure 3, we have an approach curve for phase and amplitude. As you can see, the amplitude gets smaller as the scanner approaches the sample (from right to left on the graph). This makes sense, because once the cantilever reaches the sample, its amplitude will decrease, since contact with the sample will impede its movement.

Image taken from [X. Chen et al., *Interpretation of tapping mode atomic force microscopy data using amplitude-phase-distance measurements.* Ultramicroscopy 75, 171-81 (1998).]

The Oscillating Beam

The theoretical model with which we describe the cantilever's motion is *the oscillating beam* with one end fixed and one end free to oscillate, as seen in Figure 4. Vibrations are represented as transversal displacements along the *z*-axis. The equation of motion describing of this beam is (see Fig. 4)

$$\frac{\partial^4 z}{\partial x^4} = -\frac{1}{a^2}\frac{\partial^2 z}{\partial t^2} \quad \text{with } a = \sqrt{\frac{Eh^2}{12\rho}}.$$

where ρ is the density of the beam. Solving for the *z*-axis displacement, applying the Equipartition theorem and

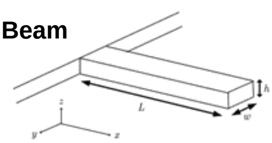

Fig. 4 – The oscillating beam

Hooke's law, one finds

$$k_{eff} \equiv \frac{\nu_i}{\nu_k}k.$$

That is, the effective stiffness of the cantilever is increased by the factor by which the drive frequency is increased beyond the fundamental.

Equation of motion taken from [Butt, H. and Jaschke, M. *Calculation of thermal noise in atomic force microscopy.* Nanotechnology, 1995.]

The Effective Stiffness Approximation

The idea behind the effective stiffness approximation is that one can drive the cantilever at an overtone, rather than its fundamental frequency, to emulate a cantilever of higher stiffness. Using the model for an oscillating beam, one discovers a relationship between the mode of the beam's oscillation, its effective stiffness, k_{eff}, and its natural stiffness, k, according to the following table.

Mode	Fundamental	1st Overtone	2nd Overtone	3rd Overtone
K_{eff}	0.9856k	6.1764k	17.294k	33.889k
Beam Shape				

Beam shape images taken from [Butt, H. and Jaschke, M. *Calculation of thermal noise in atomic force microscopy.* Nanotechnology, 1995.]

Simulated Experiments

Experiments were conducted in a computer-simulated AFM to determine if it is possible to drive a single cantilever at different modes to emulate different stiffnesses. Different stiffnesses in the same cantilever would allow for optimal data-acquisition of materials' properties and topography. So in one mode, one expects to see the cantilever merely tapping the surface, while at another, higher mode, to see the cantilever penetrating the surface.

In Figure 5, we see a cantilever's motion at two overtones. At the first, the sample is not penetrated by the cantilever, while at the third overtone, it is.

In Figure 6, the cantilever is driven at four modes. As the modes get higher, the cantilever penetrates the sample more deeply.

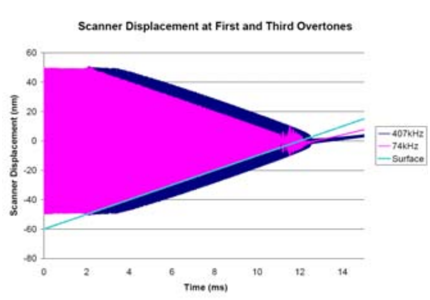

Fig. 5 – An approach curve displaying the waveform of a cantilever oscillating at its fundamental and first overtone

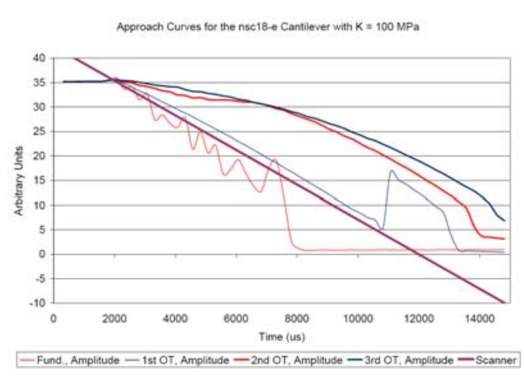

Fig. 6 – An approach curve displaying the amplitudes of the first four modes of a cantilever

Conclusions and Future Work

The computer simulations demonstrate that the effective stiffness approximation enables a single cantilever to be used to optimally acquire both topography and materials' properties data of a sample. It does this by exciting the cantilever at different modes: lower-frequency excitation modes correspond to a lower effective stiffness of the cantilever, making the cantilever optimal for obtaining topographical data, while higher modes correspond to higher cantilever stiffness, which is necessary for obtaining good materials' properties data.

This method may allow for simpler data-acquisition for AFM experimentalists because cantilevers will need to be changed less frequently, which may alleviate some difficulties, especially the problem of losing the tip's position over the sample when changing cantilevers.

However, before the method is used in practice, experiments testing this method using a real atomic force microscope should be performed, since a simulation cannot produce entirely conclusive results.