Application Note: Magnetic Force Microscopy (MFM) with AFM

By Gary Williams

Magnetic Force Microscopy is an extension of the imaging techniques based upon the Atomic Force Microscope (AFM). A member of the scanning probe microscope family, the AFM utilizes a computer-controlled feedback loop to control a mechanically etched silicon probe over nanometer sized areas. The AFM technique is sensitive to the small surface forces associated with the atomically sharp tip and is able to achieve even single nanometer resolution. AFM is now used to routinely characterize surface roughness for the manufacturing processes, defect review of pitting or particulates, and increasing use in characterizing the qualities in the solar panels and material properties. Research regarding DNA molecules, quantum particles, nanofibers, nanolithography, and the structural tuning of nano-porous structure is opening doors to insight in nanotechnology.

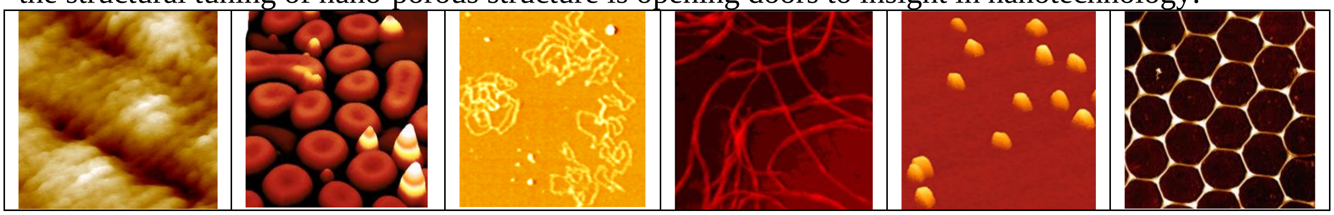


Figure 1a-1f - Images from left to right of Si wafer (courtesy of John Moore, Daetec), solar film (courtesy of Dr. Sue Carter, UCSC) DNA molecules, nanofibers of banana (courtesy Dr. Juan Meza Meza, Columbia University) 1nm diameter quantum particles (courtesy of Dr. Mike Gordon, UCSB), (courtesy Dr. Juan Meza Meza, Columbia University), and nanoporous structure.

Of particular interest for the AFM is the ability to create signal generating opportunities for the probe as it is rastered across the sample surface or used in a controlled position scenario.
The ability of the hard drive industry to regularly increase the density of its disk though the 1990s was largely due to the ability of the research engineers to study the relationship of the surface texture to domain structure of the recorded signal. Quality of the recording head and the relationship to the air bearing surface were all valuable measurements to improve the manufacturing process for an increasingly difficult market to maintain a competitive edge. Typical MFM applications include imaging the magnetic bit profile of data stored in magnetic media, and imaging the fields near Bloch wall boundaries and other domain boundaries in magnetic solids.

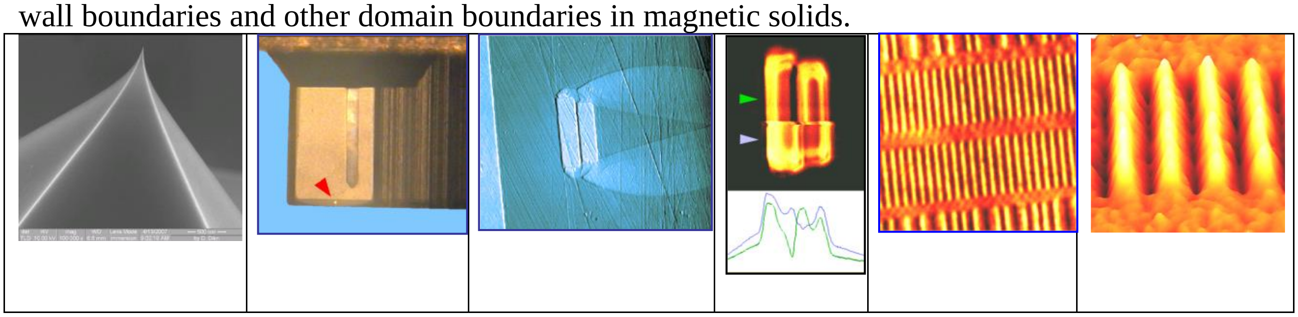


Figure 2a-2f - Images from left to right of an AFM tip (courtesy of AppNano.com), MFM probe near magnetic pole (Surface topography of the magnetic read-write head (brighter regions are higher),image and line profile cross section of the pole with a current applied of +30mA and then a reversal to -30mA during the scan (green and white arrows respectively. Images by Dr. Larry Silva, Ambios). 20µm area of MFM data on a 100Mb Zip Drive tape surface, 5µm 3d.

Weak magnetic materials with a low coercivity are more difficult to image by MFM than hard magnetic materials, which generally have much stronger fields. The AFM topology image at left shows a portion of a magnetically soft 110 nm thick iron film patterned on a GaAs substrate. Between the Fe regions a small amount of residue can be seen on the GaAs surface-- material left behind from the patterning process.

In the MFM image of the same area, shown below, the magnetic domain structure of the iron is revealed. The magnetic probe clearly shows the Bloch lines between the domains. The contrast in this image is due to shifts in the phase of the cantilever's vibrational motion with respect to the drive signal.

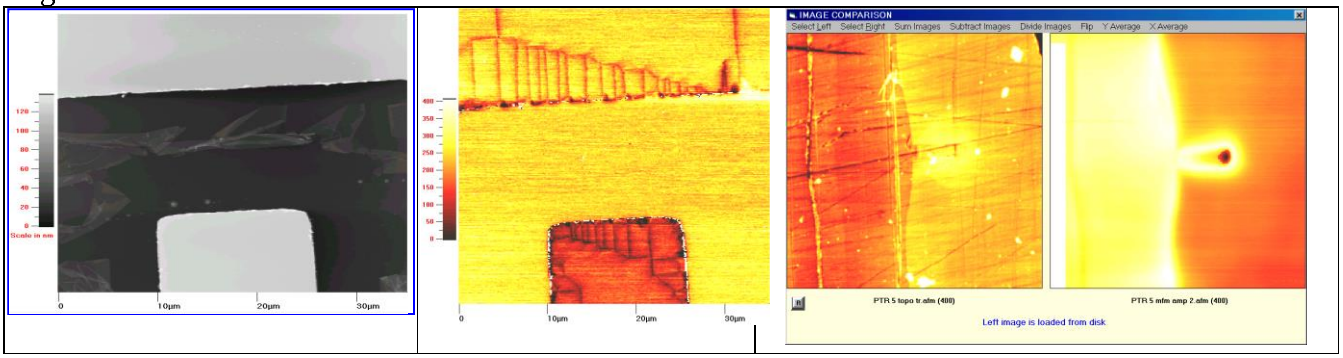
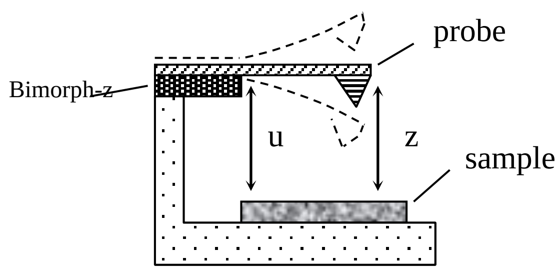


Figure 3a-3c- The magnetic data were taken with a standard MFM cantilever, scanning the probe 50 nm above the surface at a rate of 0.6 Hz. The sample was provided by Dr. Neil Curson, Cavendish Laboratory, U.K. Magnetic Recording Head Pole Tip Recession topography and simultaneous MFM signal. Sample from Seagate Hard Drive

A thin film of magnetic material is evaporated onto the surface of the AFM probe as it is still facing upward on the wafer or strip that it was manufactured on in the MEMS process. A typical coating is an alloy of Cobalt and Chromium. A radius of 40nm is the result of a film that measures 15nm to 30nm in thickness. A magnetic field is applied perpendicular to the surface of the tip, as the field needs to flow from the very end of the tip. A continuous film is also necessary for good imaging, as chipped or worn MFM tips will yield poor resolution and sensitivity. Very sensitive films require a



non-magnetic probe holder when levels of signal detection are very low.

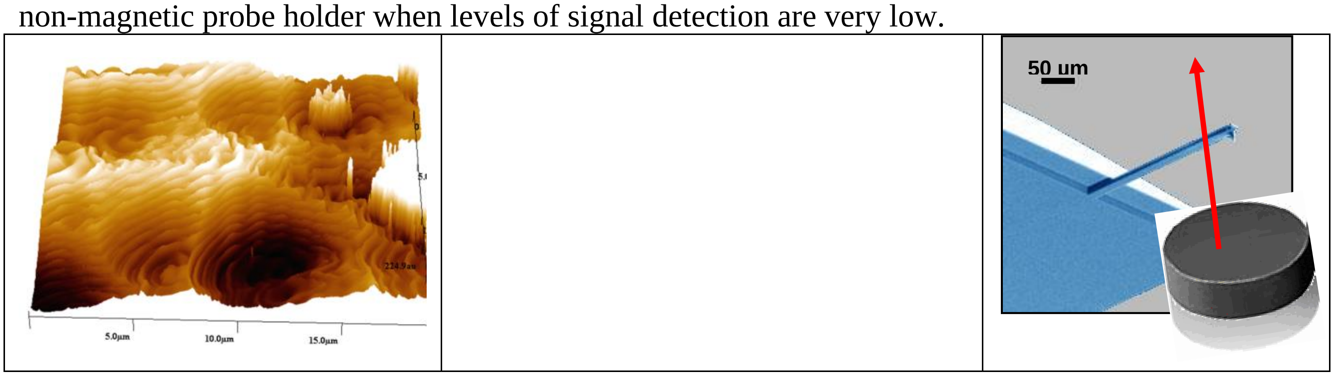


Figure 4a-4c- Thin film on brass substrate (image courtesy of Hi-Tech Instruments, Malaysia) Magnetic Recording Head Pole Tip Recession topography and simultaneous MFM signal. Drawing of MFM probe relationship to sample surface where u represents the lift distance for Terrain Mode imaging. Magnet film on probe may be excited using and inexpensive rare earth magnet with a vertical field.

The probe records the surface topography and repeats the shape at a consistent distance above that terrain. In the Terrain Mode of MFM, the effect of surface tilt and topography is reduced as the probe deflection related to surface feedback positioning is reduced. The probe should be magnetized with a rare earth magnet with electron flow that is perpendicular to the probe tip. On the Radio Shack Super Magnet Model: 64-1895 Catalog #: 64-1895, the mounted probe on the metal substrate may be placed on the flat and round side of the magnet for several minutes to create a stable field within the MFM film on the probe tip. Vertical polarization in this method works best for most samples and will be necessary to reproduce the results on the standard sample of Zip disk magnetic tape on glass.Terrain mode imaging is especially important when imaging films with multiple step structure. The example of the magnetic ferrite film in figures 5a and 5b show a continuous pattern of MFM field strength and domain shapes that do not relate to the topography data that was acquired at the same time. When the magnetic domain signal closely relates to the topography structure, it is common that the field is being influenced by the surface topography and not material differences.

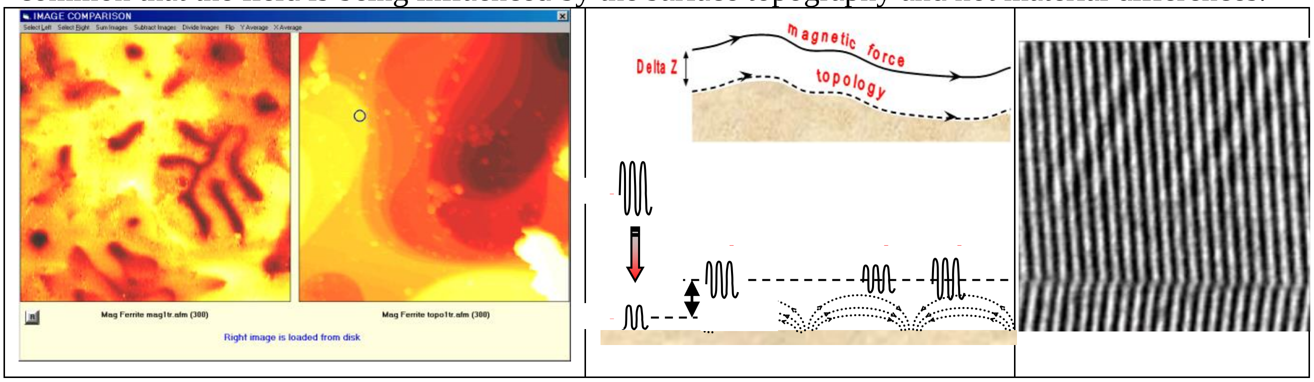


Figure 5a-5d – Simultaneously acquired MFM signal (left) and surface topography of a Magnetic Ferrite film (sample courtesy of the Univ. of Heidelberg), The probe's oscillation is dampened or expanded in relation to the magnetic interaction to the surface. The phase change of the magnetic probe is also a useful MFM map. Digital Video Tape – a Delta Z of 125nm of adjusted for the best distance above the surface.

Aside from the Terrain mode that can measure the surface topography and equivalent height magnetic field of that area, the AFM is capable of collecting the phase change that the probe feels as it is rastered across the surface. A Constant height mode may be selected to collect a quick magnetic profile across each line at a constant Delta Z height above the sample. The tilt of the sample and roughness of the sample surface should be well understood before using the Constant Height mode, but the results are often the most sensitive to small domains.

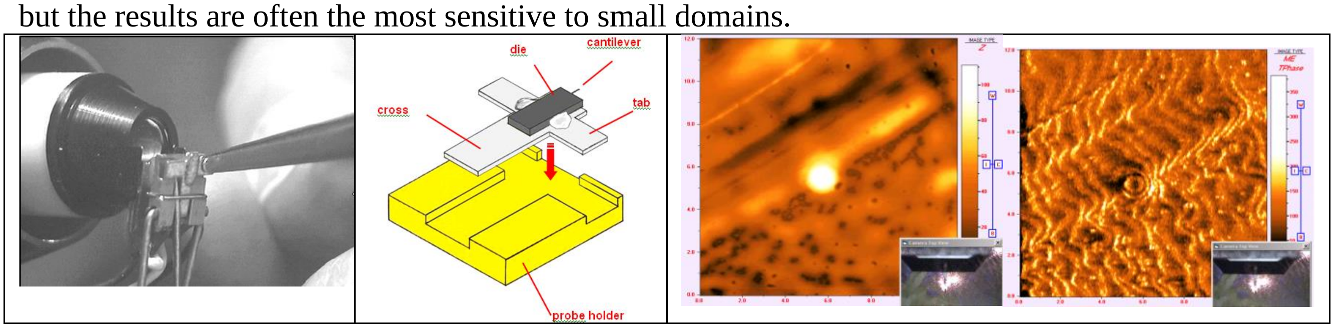


Figure 6a-6d – Scanner probe non-magnetic clip with AFM probe mount. Schematic of silicon cantilever mounted onto an iron cross to be held in place by a clip or the magnetic probe holder of the standard AFM. YiG on GGG (X-axis) Topography of the surface where the bright spot is a bump and the dark spots are erosion. The right hand image is the MFM signal showing a coarse domain structure and a signal strength of ~375 (sample courtesy of Oakland University).

A non-magnetic probe holder employs a clasp instead of a magnetic probe holder that utilizes small magnets. The magnetic field from these magnets is weak enough to allow MFM imaging of high coercivity materials (> 100 Oe) and standard MFM probes are good for most work. Many specialized probes are available from various vendors that might be useful for specific studies of high moment or low coercivity. The fine structure of the film in figure 4a has a peak value near 300 Oersted. A soft cantilever with a resonant frequency around 60kHz is the best for sensitivity to the magnetic field. The slower resonance requires a slower scanning speed and lower resonant peak to conserve the magnetic film quality and sharp point of the cantilever.

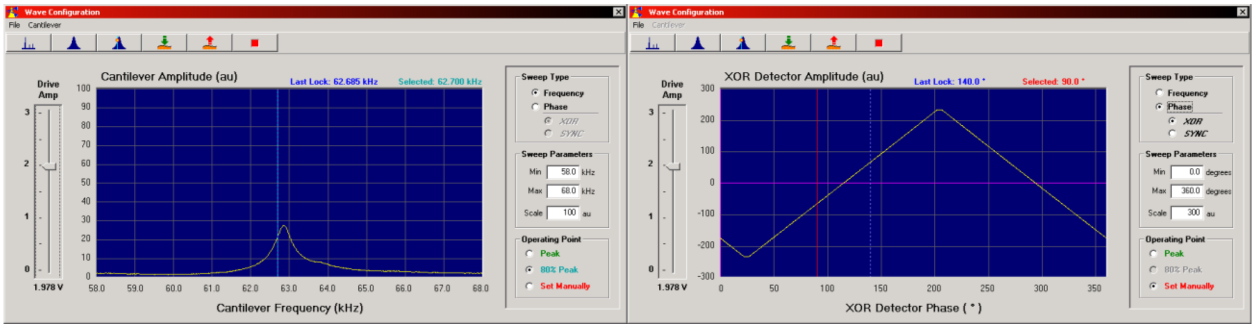
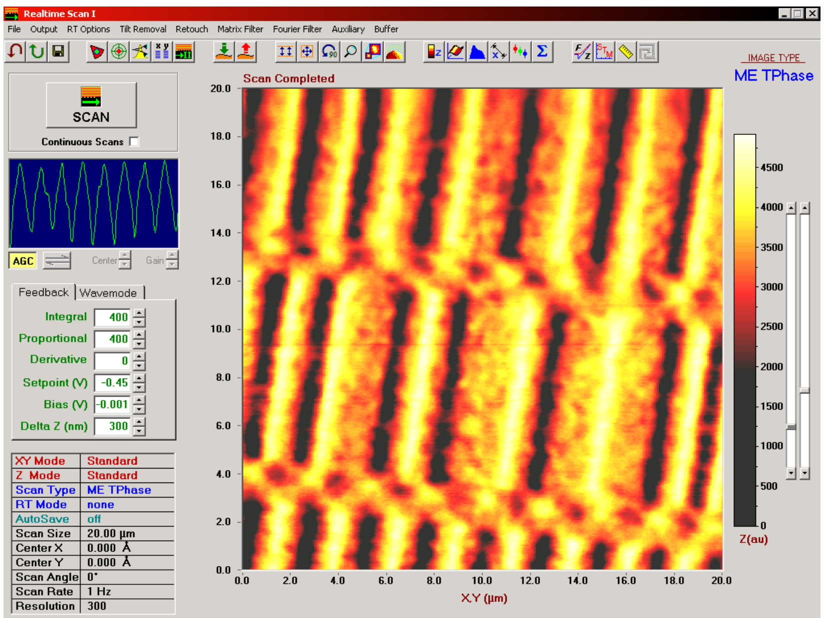


Figure 7a-7b – Resonant peak and amplitude adjustment for probe sensitivity. The phase angle deviation from the piezo driving phase should be adjusted to the middle position of the slope for the greatest sensitivity.



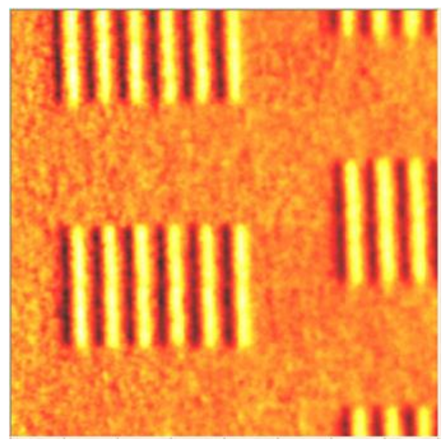
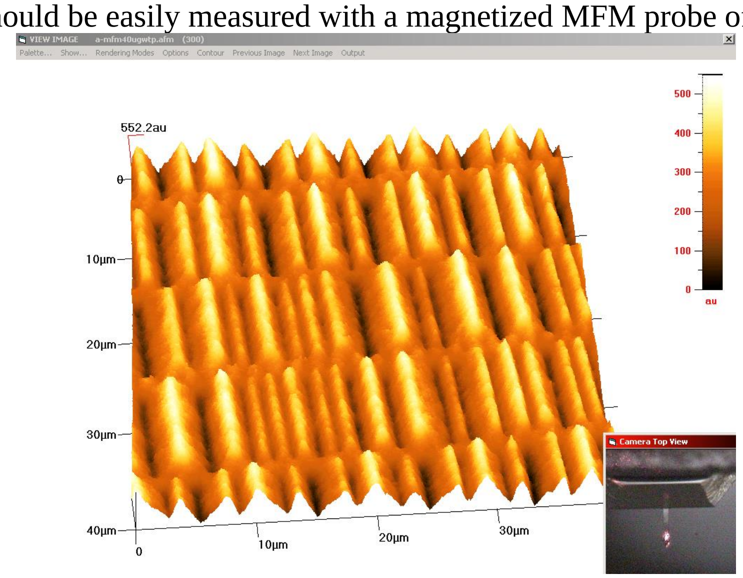


Figure 8a and 8b – Terrain mode Phase shift image of 100Mb ZIP drive tape 20µm area. Unwritten 20µm area.

The 100Mb ZIP tape will typically measure up to 5000 au (arbitrary units from the photo detector) and should be easily measured with a magnetized MFM probe of fair to good sharpness.



An Introduction to MFM Theory

The simplest starting point when describing the interaction between a magnetic probe and an external magnetic field **B** is to assume the tip acts like a constant point dipole **m** moving through the external field of the sample. In this case the force at the end of the cantilever is just

This approximation is acceptable when the size of the effective tip dipole is small compared to the spatial

$$\mathbf{F} = \nabla(\mathbf{m} \bullet \mathbf{B}) \quad .$$

gradient changes in the field. More generally, any small volume element dV in the tip has a local magnetization **M**, and a differential dipole moment **M**dV, and it experiences a differential force d**F** of the same form as given above. The total force on a tip with arbitrary magnetization is found by integration of the differential forces over the tip volume:

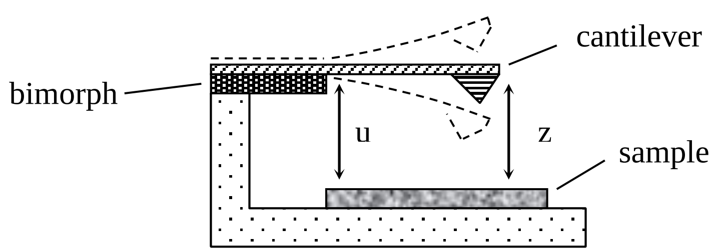
$$\mathbf{F} = \int \nabla(\mathbf{M} \bullet \mathbf{B}) dV \quad .$$

For our purposes it will be sufficient to continue with just the simplest model, where the magnetic tip is a point dipole oriented along the **z** (vertical) direction. As the probe is rastered over the surface there will only be a vertical force

$$F_z = m_z \frac{dB_z}{dz}$$

on the dipole, which will bend cantilever up or down in unison with the vertical field gradient.

In most cases the detector signal produced by the cantilever flexure in a field gradient is very small, and therefore is not used as the recorded MFM signal. Instead, the sensitivity of the detection scheme is increased by setting the probe into vibration and measuring the AC changes in either the amplitude or phase of the cantilever as it is rastered. The mechanical model sketched below illustrates the AC modulation scheme.



The piezoelectric bimorph is driven into oscillation at frequency ω with a small amplitude α, so the back end of the cantilever oscillates vertically as

$$u = u_o + \alpha \sin(\omega t) \qquad (1)$$

where u_0 is the static position. The best MFM images are obtained with ω at or near the resonant frequency of the cantilever, so the probe-end of the cantilever will vibrate with the same frequency as the bimorph but at a much greater amplitude. The position of the probe-end of the cantilever is given by

$$z = z_o + s \quad (2)$$

where the offset from the static position z_o will be a phase shifted sinusoid of the form

$$s = A \sin(\omega t - \theta) \quad (3)$$

as long as the amplitude is low enough for the motion to remain harmonic, and just in the fundamental vibration mode. Applying basic mechanics, the equation of motion for the probe-end of the cantilever is

$$\mathrm{m}\frac{d^2 z}{dt^2} = -\gamma \frac{dz}{dt} + k(u - z) + F_z \quad (4)$$

with the new variables being the effective cantilever mass m, the oscillation damping term γ, and the effective cantilever spring constant k.

The conditions which allow the probe tip to be approximated by a point dipole also allow the magnetic force F_z to be approximated by its value at the static position of the probe $F_o = m_z\,[dB_z / dz]_{z=zo}$ plus its first order derivative at the static position $F_o' = m_z\,[d^2B_z / dz^2]_{z=zo}$. That is

$$F_z = F_o + sF_o' \,. \quad (5)$$

In the static $\omega = 0$ equilibrium condition the spring constant force must balance the bending force from the external field gradient. In equation form,

$$F_o = k(z_o - u_o) \,. \quad (6)$$

At this point it is helpful to summarize before proceeding further. What the cantilever is physically doing as the tip is rastered over the sample is bending up and down slightly by a DC amount z_o in unison with the magnetic field gradient F_o, while at the same time oscillating sinusoidally about z_o with amplitude A , and phase θ with respect to the bimorph motion. In normal MFM the DC information is discarded. An AC detection scheme measures what happens to s as the probe is scanned.

The equation of motion for s is found by combining Equations 1, 2, 4, 5, and 6, and re-arranging terms.

$$\mathrm{m}\frac{d^2 s}{dt^2} = -\gamma \frac{ds}{dt} + (k - F_o')s = \alpha \sin(\omega t) \quad (7)$$

This is readily recognized as the standard equation for a damped, forced harmonic oscillator. Notice that the spring constant for the system is shifted from k to $k' = (k - F_o')$. In the approximation that the probe tip is a point dipole, the resonance frequency of the cantilever changes as the *second derivative* of the stray field changes. Qualitatively speaking, if the sign of F_o' is negative then $k' > k$, and the effective spring constant increases. The force from the magnetic field pushes in the same direction as the mechanical spring force, as if there are now two springs acting in parallel, lowering the amplitude of the cantilever vibration. Conversely, if the sign of F_o' is positive then $k' < k$ and the force from the magnetic field pushes against the mechanical restoring force of the spring, softening the spring action. The cantilever vibration amplitude increases when F_o' is positive.

Taking the model a step further, Equation 7 can be solved to predict the best operating frequencies for imaging the surface magnetic structure with either the cantilever phase signal or amplitude signal.

The vibration amplitude as a function of bimorph frequency ω and the second derivative of the field $F_o' = d^2B_z / dz^2$ is

$$\left|\frac{A}{\alpha}\right| = \frac{1}{\left[(\omega / Q\omega_o)^2 + \left[(\omega / \omega_o)^2 - 1 + (F_o' / k)\right]^2\right]^{1/2}}$$

and the phase shift is

$$\theta = \tan^{-1}\left[\frac{(\omega / Q\omega_o)}{(\omega / \omega_o)^2 - 1 + (F_o' / k)}\right] .$$

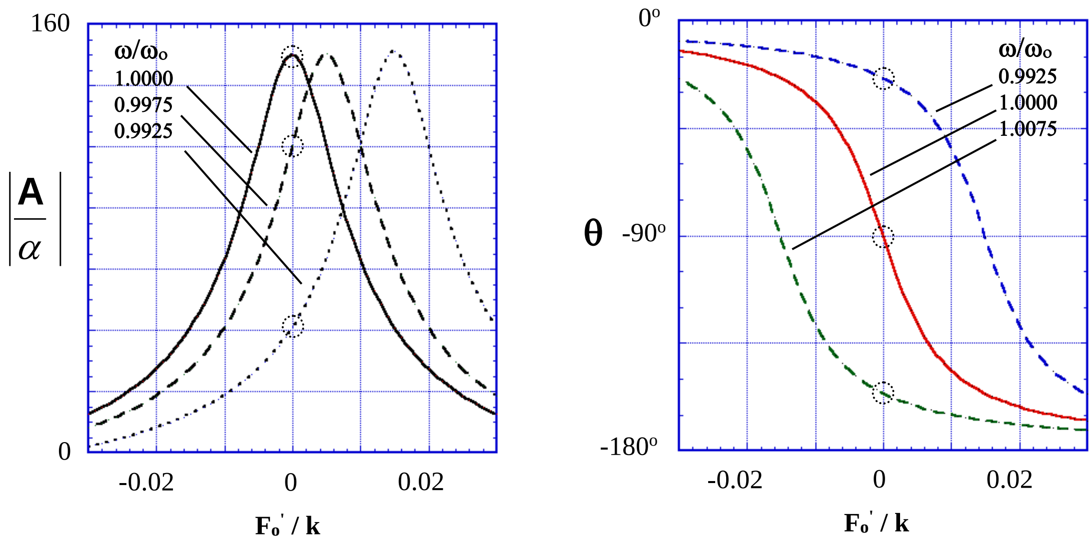


Figure 1

In these equations the damping factor γ has been substituted out via the relation $\gamma = m\omega_o/Q$, where Q is the mechanical "Q" of the cantilever vibrator and ω_o is the free resonant frequency $\omega_o = (k/m)^{1/2}$ of the cantilever.

Graphs of $|A/\alpha|$ and θ are given below. A cantilever mechanical Q of 150 has been assumed. The abscissa is the strength of the magnetic interaction F_o' normalized against the spring constant k of the cantilever.

The left graph shows that in the vicinity of small magnetic effects, where $F_o' / k \sim 0$, the cantilever vibration reaches its greatest amplitude when it is driven at the free resonance frequency w_o. The sensitivity of the MFM signal is very poor at this frequency, however, because the rate of change in A with F_o' (slope of the curve) is zero. The best sensitivity is achieved when the slope is steepest, and this occurs when $w/w_o = 0.9975$. Expressed in terms of the cantilever vibration amplitude, the best frequency to choose is the frequency at which A is approximately 80% of the peak amplitude. Notice that the slope of the curve is fairly constant over a small range of F_o' / k about this frequency, so the measured value of A appearing in an MFM image scan can be interpreted at being fairly proportional to the second derivative of the field d^2B_z / dz^2 .

The right graph shows that in the vicinity of small magnetic effects the phase signal achieves its highest slope and best sensitivity at the free resonance frequency $w/w_o = 1$. At this frequency the amplitude of the cantilever vibration is at its maximum, and the phase shift is -90º. Notice that the slope of the phase curve is fairly constant over a wider range of F_o' / k than the amplitude curve. The measured value of θ appearing in an MFM image scan can also be interpreted as representing the second derivative of the field d^2B_z / dz^2 .

The predictions of any model of a physical system are limited by the extent to which they accurately reflect the real world. The model presented here is a good starting point, but it has its limitations. For further information you may wish to consult the following references:

Scanning Probe Microscopy and Spectroscopy, Methods and Applications Roland Wiesendanger, Cambridge University Press, 1994.

Scanning Force Microscopy, with Applications to Electric, Magnetic and Atomic Forces Dror Sarid, Oxford University Press, 1994.

Scanning Probe Microscopy and Spectroscopy, Theory Techniques, and Applicatons Dawn Bonell, Wiley-VCH, 2001.