MFM and EFM for AR MFP-3D

MFM

MFM functions/parameters

Magnetic Force Microscopy (MFM) detects the magnetic force or the magnetic force gradient between the magnetised cantilever tip and the sample.

Contrasts can be observed in MFM in shifts in amplitude, phase and frequency. Frequency shifts are proportional to the phase. In the newer MFP-3D software (such as versions 101010) there are phase lock loops that can be used in Nap mode. An example of a phase image in nap mode is displayed in Figure 1.

The tip-sample distance is important in Nap mode (measuring magnetic forces) as short range forces can influence the tip (ie/topographical features). A delicate balance needs to be achieved. Too high a delta height decreases contrast. A low delta height achieves the best lateral resolution. This can mean operating in a negative delta height. The topography setpoint is piviotal in MFM imaging as a reference point. The averaged tip-sample distance while imaging is determined firstly by the size of your free air amplitude before the engage fuction (button) is set. Secondly, is the the dampening of the amplitude with the setpoint setting. Tuning to an amplitude of around 1 V (which is standard), the free air amplitude is 100 nm. If your setpoint is lowered to 500 mV, the on-surface amplitude (tapping mode) is 50 nm. The base of the cantilever then is 25 nm above the surface. This means that in the Nap panel if a 25 nm delta height is chosen, the tip is actually 50 nm above the surface.

Normally, MFM and other electronic modes are operated in attractive mode. Operating in attractive or repulsive mode will vary tip-sample distance in relation to the setpoint (as mentioned above). This will change the amplitude image and the shifts in phase. To gain the minimum free/setpoint amplitude ratio, repulsive mode is best. It is best to set-up by taking a force curve while setting parameters in Nap mode. Then find the InVOLS value. Adjust drive, free air and setpoint amplitudes to get a good repulsive mode image. Use the InVOLS value to find an appropiate drive amplitude for Nap mode (Parm Swap side in Nap Panel) that provides a good signal. For rough samples this value may need to be adjusted to raise the delta height.

Operation in second resonant mode

Do a thermal tune before imaging to find the first and second resonant frequency. The second drive frequency can be set for Nap mode (MFM mode). Remember to adjust for 5% off the actual resonant frequency. Select frequency as a Channel in the Channel panel. Test by selecting the FM feedback box on in the Nap Panel.

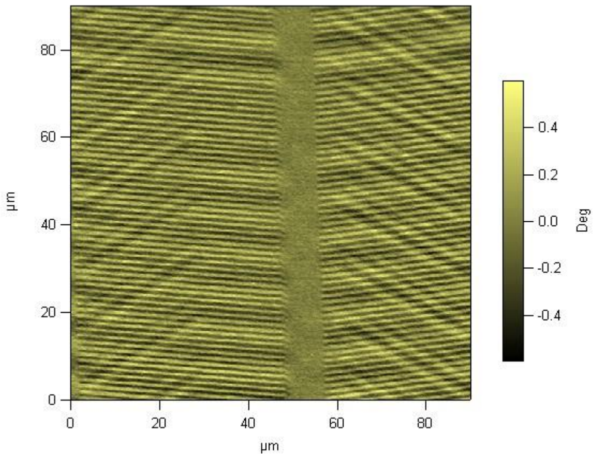


Figure 1: Nap Phase image of a Seagate hard dive.

Measuring the lateral gradient of the magnetic field $\left(\frac{\partial^2 Hx}{\partial z^2}\right)$ can be done by magnetising the probe in the lateral direction. The expanded expression for magnetic energy is $U_m = -m \cdot H$ where m is the vector moment of the cantilever tip and H is the sample vector field. The magnetic force between the tip and sample can be measured by the gradient of the magnetic energy. The force gradient (what AC mode MFM measures) is $F' = mx\frac{\partial^2 Hx}{\partial z^2} + my\frac{\partial^2 Hy}{\partial z^2} + mz\frac{\partial^2 Hz}{\partial z^2}$. This means that the tip can be magnetised along a particular axis which provides different magnetic force data (nap phase data) of the sample due to the effects of the cantilever and tip motion/reactions.

The cantilevers used for MFM scanning are MikroMasch NSC14/Co-Cr cantilevers. The bulk material is n-type silicon (phosphorus doped) coated with a 60 nm thick Cobalt layer on the tip and back of the cantilever. The cobalt layer is formed as a polycrystalline film. This allows a steady permanent magnetisation in the direction of the tip axis. The cantilevers are pre-magnetised but require additional magnetisation prior to use by a strong (rare earth) magnet. The cobalt coating is further coated by a 20 nm chromium layer as an oxidation shield.

Values

Tip radius with coatings
90.0 nm

Coercitivity (Hc) of the coating
300-400 Oe.

Full tip cone angle
40°

Tip aspect ratio
more than 3:1 (4:1 typical)

Total tip height
20-25 µm

Coercivity

The magnetic field in permanent magnets, such as rare earth magnets, have a particular vector (magnitude and direction) associated with it. Coercivity is a measurement of an opposing field in the reverse direction that is required to zero the magnets magnetisation. Remanence is the measure of the magnetic field that remains after the opposing magnetic field 'zeros' the magnetisation. An alternating (opposing) magnetic field applied to a magnet or magnetic material changing the existing magnetisation will trace out a hysteresis loop due to the closed field loops of the magnet field, Figure 2. This produces an incomplete cancelation of the entire magnetic field of the material. This is also due to the magnetic domains and boundaries within the magnetic material. A 'magnetic memory' is then produced in the magnetised material. This is a common property in ferromagnetic materials. This effect is present in magnetic force microscopy cantilevers. Pre-magnetised cantilevers retain a memory of the field direction and a residual magnetisation, thus are readily re-magnetised.

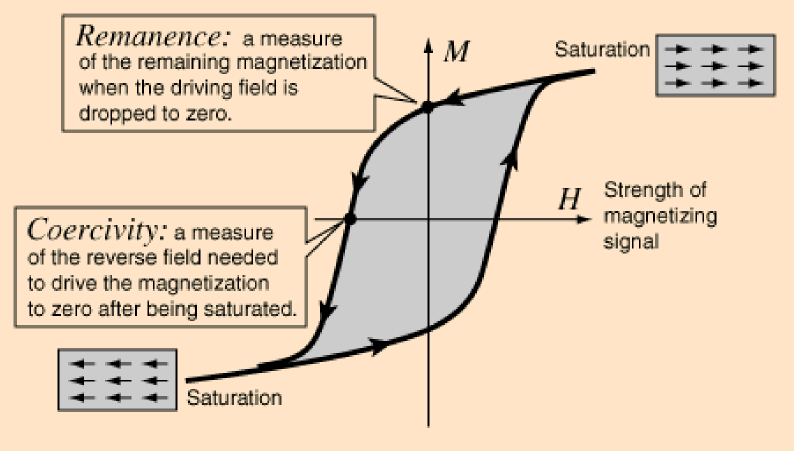


Figure 2: Hysteresis loop produced in the 'cancelling' of a material's magnetism.

Relating the concepts of coercivity and remanence to a magnetic cantilever is important to the interpretation and anomalies of MFM data.

Figure 3 shows a horizontally mounted (in relation to the sample surface, that is, parallel to the sample surface) **non**-magnetised MFM cantilever.

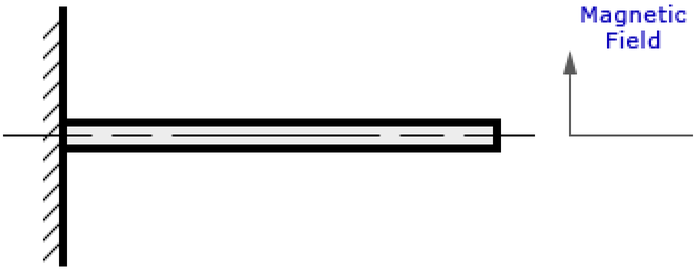


Figure 3: Non-magnetised MFM cantilever.

Figure 4 shows a magnetised MFM cantilever. The cantilever is deflected from the surface due to the magnetic forces. In this example, it is assumed that the cantilever is magnetically saturated.

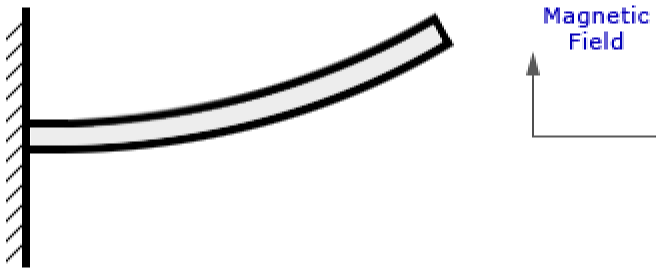


Figure 4: Magnetised MFM cantilever.

An opposing force is required to return the cantilever to its horizontal state, figure 5. This opposing force returns the cantilever to a 'neutral' state so no flexion or material grain stress is present on the cantilever. The opposing force is in the form of the coercivity. This coercivity is abbreviated as Hc.

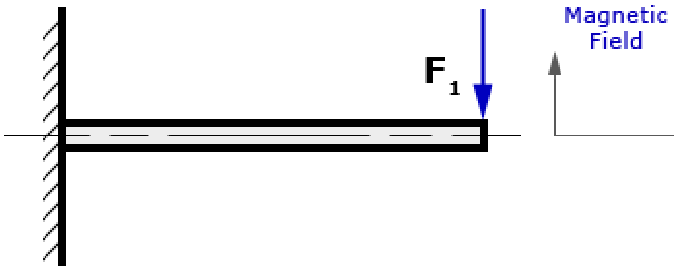


Figure 5: Magnetised cantilever returned to horizontal by an opposing force.

Materials often possess properties referred to as elastic or plastic. An elastic property in a material means that any deformation of that material is reversible. That is, it will return to its original position when the force used to deform it is removed. Plastic properties refer to an irreversible deformation, in that the material will not return to its original state/shape. In the case of cantilevers, it is obvious that the properties are more elastic rather than plastic. There is a limit to the elastic properties of cantilevers. Bending/flexing the cantilever past a certain flexure angle would cause a permanent (plastic) deformation and the cantilever would not return back to its original state. Therefore, the forces applied to the cantilever, in this case, the opposing force to return the cantilever to its horizontal state, need to be controlled and limited. Elastic/plastic properties have influences on the stiffness and control of the cantilever. In the case of magnetic cantilevers, these properties affect the force parameters applied to the cantilever, such as the opposing force required to return the cantilever to its horizontal position.

For an elastic cantilever, removing the opposing force (the reversing magnetic force, Hc), the cantilever would return to the state shown in figure 4. A plastic cantilever would not recover after Hc is removed. The elastic magnet requires greater force in order for it not to recover, for it to be overcompensated. Hc that causes the material's magnetic properties to 'null' out is close to the same magnetising force that permanently demagnetises the magnetic cantilever. A much greater force is needed to permanently demagnetise the magnetic cantilever. In an elastic cantilever this may require a force that may flex the cantilever beyond its elastic property range and cause a permanent (plastic) deformation of the cantilever.

The materials that make up the cantilever are not the only factors that give it the elastic or plastic quality ratio. The grain/fibre orientation, the magnetic vector, the overall shape and the ratio of different materials (layers) that make up the magnetic cantilever.

http://www.mceproducts.com/knowledge-base/article/article-dtl.asp?id=86

EFM

Phase

The phase is the time difference (lag) between the cantilever response (adjustment in response to stimuli) and the actual adjustment to the shake piezo (Sine waves in the form of AC voltage). The phase of a signal is defined in relation to the original signal. When the signals match (the peaks and troughs are in-line) the signals are in-phase (zero degrees advanced or retarded). Signals differing by half a period are out of phase by 180 degrees (π).

Input i and Input q

In the main channel panel in the MFP-3D software, input q is the out of imaginary part of the output from the lock-in amplifier. The amplitude (r) and phase (θ) are outputs from the lock-in amplifier. These outputs indicate how large a signal exists at the reference frequency, and the phase lead or lag of that signal relative to the reference signal. These are the outputs expressed in polar coordinates.

These values can be expressed in Cartesian (xy) coordinates. These outputs are x = r*cos(θ) and y = r*sin(θ). Electrical engineers usually describe these as q and i respectively rather than x and y. During the main scan, these values are related to the interaction between the tip and the sample. The input i is related to the energy conserved as the tip and sample interact. This is energy returned elastically to the tip as it taps on the sample. The input q is related to the forces that are dissipated from the tip into the sample, usually as heat.

The distance to the I-Q pair is the amplitude, the angle to the pair is the phase.

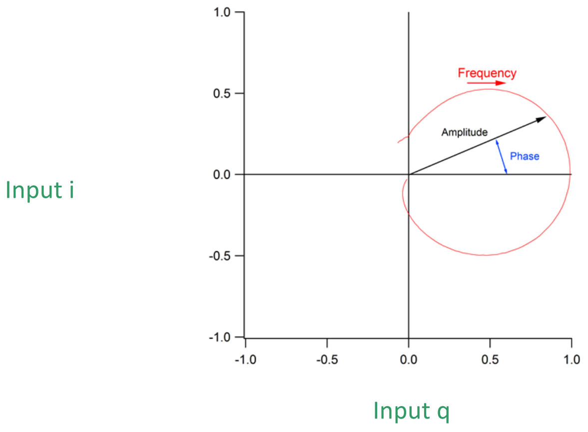
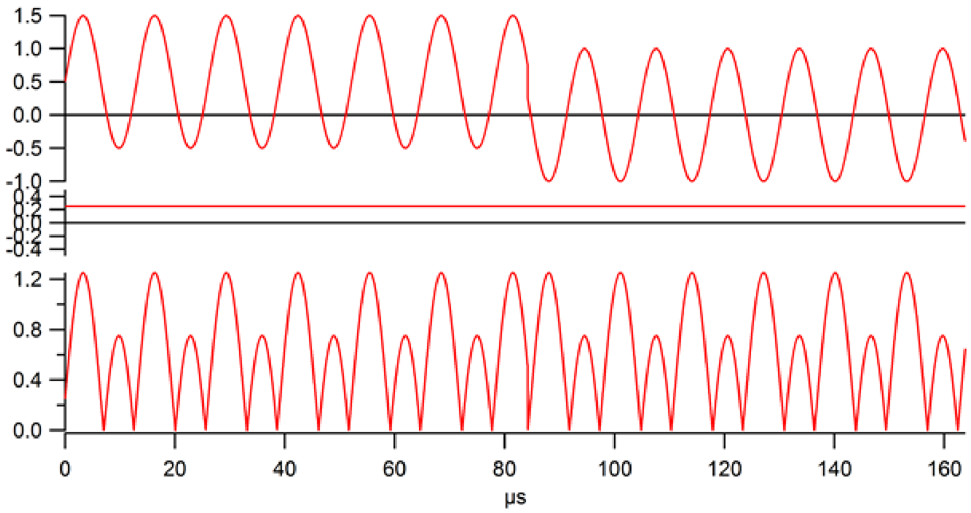


Figure 6: Graph of input i and input q versus amplitude and phase. Input i is the vertical (y) axis and input q is the horizontal (x) axis.



In the above graph, the drive wave is ~0.25 V more positive than the sample in the first half, and ~0.25 V more negative than the sample in the second half. In the first half the forces are in phase with the drive, in the second half they are 180 degrees out of phase.

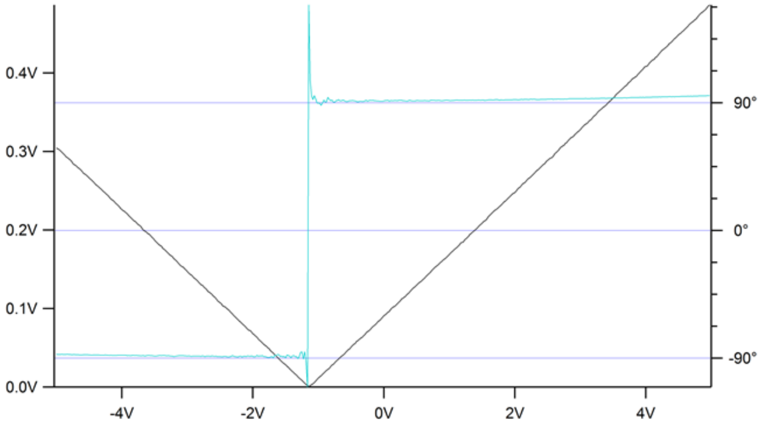


Figure 7: Sample graph of the Tip Voltage Offset Tune button.

This is the graph that you see when you hit Tip Voltage Offset Tune button (you have to hit the Setup button to get this to show). In this case my sample has a potential of a little less than -1V. The amplitude does nice linear increase as the voltage difference increases, but it gets bigger whether the difference is positive or negative. The phase jumps from -90 to 90 when the potential voltage is crossed, but doesn't actually contain any information about how big the difference is, just the sign. This means that it actually won't work well as the input for a feedback loop.

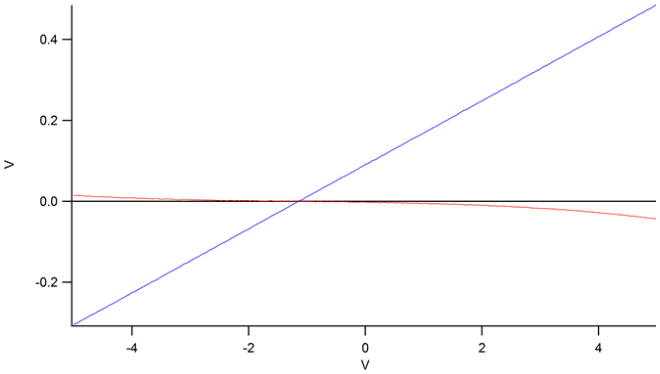


Figure 8: I and Q tune for Tip Voltage Offset Tune. Q is blue trace.

The other graph that pops up when you run the Tip Voltage Offset Tune is the I and Q tune. This is basically the same graph as the one above it, except I and Q are the rectangular version of the signal, whereas Amplitude and Phase are the polar coordinates. At last we have found what we are looking for. Q, which is the blue trace, is the perfect input for our feedback loop, so that is what we use.

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This graph is just a simple diagram of I and Q versus amplitude and phase. This shows I and Q captured during a cantilever tune. I is the vertical axis and Q is the horizontal. The distance to the I-Q pair is the amplitude, the angle to the pair is the phase. In the controller an FPGA (Field programmable gate array: An integrated circuit/semiconductor device configured after manufacturing for a specific function/purpose) calculates I and Q, then a DSP (Digital signal processor: Specialized microprocessor with an optimised design for the fast operational needs of digital signal processing) uses those to calculate amplitude and phase.