Diamagnetic Lateral Force Calibration (D-LFC)

This is an interesting lateral force calibration procedure from the source:
http://www.imelab.org/Calibrator/diysteps.html

Most AFM thin film coated cantilevers have typical lateral spring constants in the100 nN/nm range and an operational range within 100 nm of deflection. A compliant load cell with a spring constant of ~ 100 pN/nm can accurately calibrate the AFM force constants. Applying a small known force on the cantilever-tip, the load cell should stay "freely" in air without touching any other local components (otherwise it will introduce extra non-controllable adhesion and friction forces).

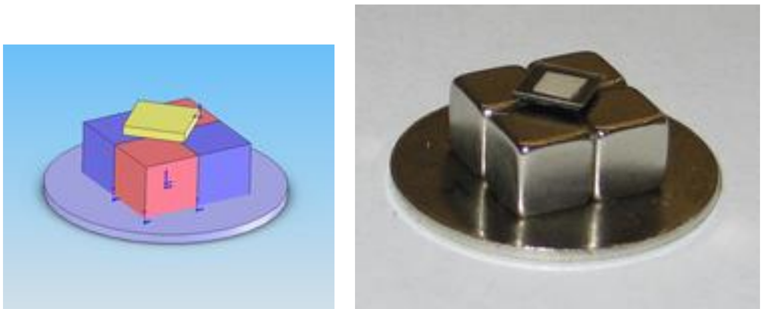

Figure 1: A schematic and a picture of a D-LFC set-up.

Magnetic Levitation System

Levitation systems using magnets and graphite have been applied in tiltmeters /seismometers for over forty years. These are interesting set-ups as the small suspended mass is usually without any source of friction (except for air drag) and that the motion of the suspended mass is very sensitive to the external excitements. These two features make the diamagnetic levitation system an ideal for the AFM lateral force calibration. In a diamagnetic substance, the magnetic moment induced by an applied magnetic field opposes the applied magnetic field and the substance repels the source of the magnetic field, e.g. magnet, exhibits negative susceptibility. Many substances including water, protein, carbon, DNA, plastic, wood, graphite and bismuth are diamagnetic. Susceptibilities of some diamagnetic materials are summarized in Table 1.

Table 1: Values of susceptibility for various diamagnetic materials (in SI units)

Material	$\chi(\times 10^{-6})$
Water	-8.8
Gold	-34
Bismuth	-170

Graphite rod	-160
Pyrolytic graphite	-450
Pyrolytic graphite =	-85

Among these materials, graphite and bismuth display very strong diamagnetism. The susceptibility of a CVD-grown pyrolytic graphite (PG) is highly anisotropic and the susceptibility in the direction perpendicular to the basal plane is several times higher than that in the direction parallel to the plane. This strong anisotropy is useful to suspend a PG sheet in a magnetic field, balancing the gravity force, while the lateral spring constant of levitation is tuned to be small. There are two key points for a successful levitation: right materials and right setup. The levitated mass is made of pyrolytic graphite (PG). A regular cheap PG sheet is good enough for levitation, you don't need the expensive highly order pyrolytic graphite (HOPG). Strong magnets are also required, such as Neodymium-iron-boron (NdFeB) permanent magnets.

D-LFC Setup

To make the PG sheet sit still above the magnets, you need to apply to the magnetic forces in a stable way. An easy way is to use the four- magnet setup. Use four magnets and align their poles vertically and alternate such that two with north facing up and two with south facing up, diagonally.

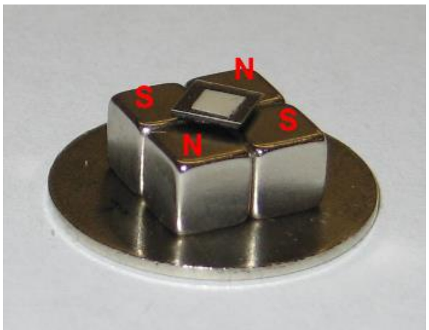

Figure 2: Four-magnet setup for D-LFC

Useful tips:

- Put this array on a sheet of steel; it will stick naturally to the steel due to its strong magnetism. This makes it much easier and safer to use, otherwise the array will try to attract everything it can adhere to;
- Before putting these magnets together, find out the correct faces corresponding to the north and the south poles; it may take a while since they are cubic
- Try to put them individually and apart onto the steel sheet first, then push them together along the surface.

Once the magnet array is ready, we can move to the next step to prepare the floating graphite sheet. Cut the pyrolytic graphite into square-shaped sheets with proper thickness and modify the top surface so that it's flat enough to be used in AFM. The pyrolytic graphite has a layered structure and is readily to be cleaved. A razor blade or a sharp knife is ideal.

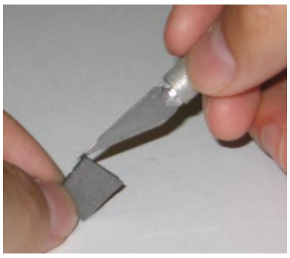

Figure 3: Cutting a pyrolytic graphite sheet with a sharp hobby knife

This is a very important step because the shape and size of the PG sheet largely determine the spring constant of your D-LFC system. The spring constant also depends on the quality of your PG sheet and the grade of the magnets. You need to figure out the right dimensions for your own application. Guidelines here are based on experience and finite element calculation:

- The PG sheet should be cut as square as possible. This makes the levitation more stable and the spring constants more isotropic. More important, it makes the translation and rotation decoupled;
- Higher grade magnet gives larger magnetic forces, hereby higher spring constants;
- Thicker PG sheet gives you more magnetic forces, but due to its weight it's closer to the magnet surfaces;
- The PG sheet loses stability when its lateral dimension exceeds certain limit. For the four-magnet setup, the limit is square root 2 times the length of the magnet cubics. The spring constant approaches zero at that critical dimension.

Because the surface of the pyrolytic graphite sheet is usually very rough, the top surface should be modified to avoid contaminating and damaging your AFM probes. It is well known that mica can be easily cleaved to offer an atomically flat surface; Gluing a thin mica sheet on top of the pyrolytic graphite sheet is a solution.

Determination of D-LFC Spring Constant

After following all the steps above, your D-LFC should almost set-up. Fine-tune by pushing the PG sheet a bit off the centre: the PG sheet will vibrate harmonically in air like a standard spring-mass system. We may notice that the vibration amplitude decays slowly, this is due to the damping effects of the air drag and eddy current. To use this D-LFC to calibrate the lateral force constants, it is necessary to know the spring constants of the D-LFC itself. We know that the motion could be described by the equation of free vibration.

$$\ddot{x}_1 + 2\zeta\omega_n\dot{x}_1 + \omega_n^2 x_1 = 0 \qquad (3)$$

By measuring the mass, vibration frequency and amplitude decaying rate, the spring constant can be calculated. So, the next step is to monitor the free vibration of the PG sheet in air then calculate the spring constant of D-LFC. Ideally, we should monitor the PG sheet position vs. time for the vibration process. There are many ways you can think of, e.g. video recording or a laser Doppler velocimeter. In our case, we use a simple setup called laser displacement tracer. The basic idea is that a sheet of a 10 mW He-Ne laser light was partially blocked by the edge of the vibrating PG. The transmitted light intensity was detected by a photodiode. A typical time trace of the amplitude using our displacement tracer is shown below:

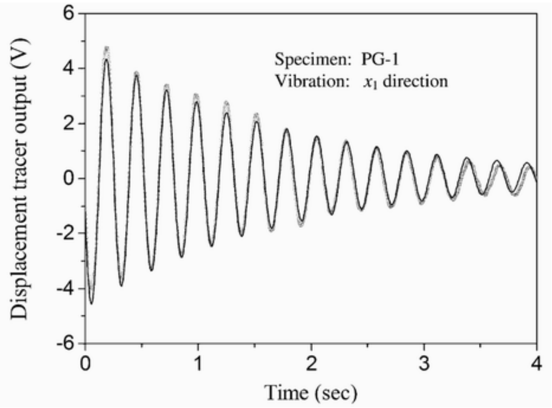

Figure 5. Time trace of the free vibration amplitude

The amplitude curve is fitted using the form of the general solution to the equation (3):

$$x_1(t) = e^{-\zeta\omega_n t}(a_1 \sin\omega_d t + a_2 \cos\omega_d t) \qquad (4)$$

where $\omega_d = \omega_n\sqrt{1-\zeta^2}$.

Once you have the values for ω_n and ζ, the spring constant of D-LFC can be calculated as

$$k_{11} = m^{(I)}\omega_n^2 = m^{(I)}\omega_d^2/(1-\zeta^2) \qquad (5)$$

where $m^{(I)}$ is the mass of the PG composite sheet.

If the damping ζ is small, which is true for most of the cases, ω_n and ω_d are approximately the same. So, instead of curve fitting, you can simply measure the vibration frequency and use it to calculate the spring constants.