DYNAMIC AFM

-1- Amplitude Modulation Mode (or tapping mode) AM-AFM

THIS IS WHAT WE HAVE STUDIED IN THE QBIO COURSE

- Constant Amplitude (feedback loop)
- Intermittent mechanical contact between tip and sample
- Tip position (z) described by non-linear harmonic oscillator → no analytical solutions, but numerical, often multiple, solutions exist

$$m\ddot{z} + \delta\dot{z} + kz = F_{interaction}(z) + F_0(\omega t)$$

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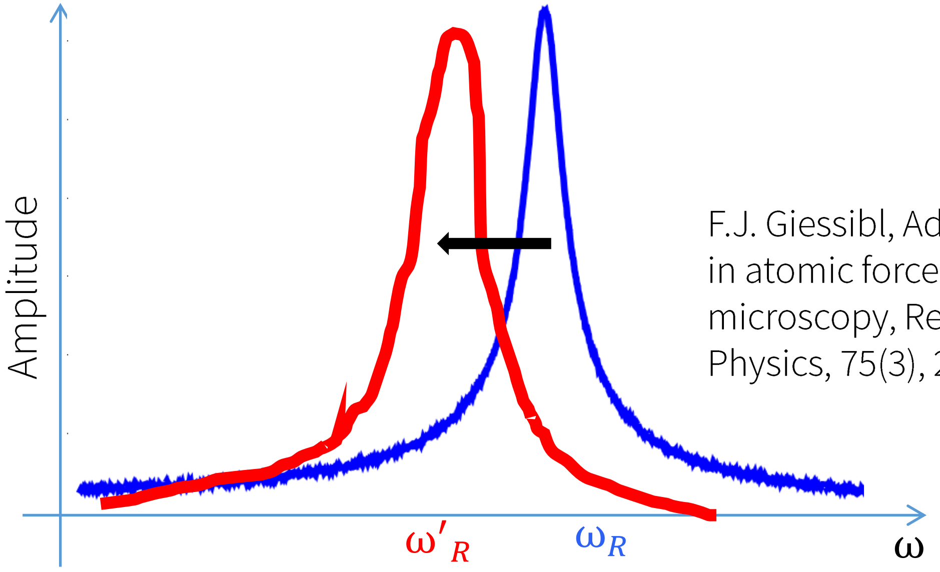
-2- Frequency Modulation Mode – FM-AFM

WE DID NOT MENTION THIS ONE IN THE QBIO COURSE

T. R. Albrecht, P. Gritter, F. Horne, D. Rugar, "Frequency modulation detection using high-q cantilevers for enhanced force microscope sensitivity", J. Appl. Phys, vol. 69, pp. 668-673, 1991

FREQUENCY MODULATION MODE

If amplitude of tip oscillation: 0.1nm – 1nm (ten times lower than in AM-AFM),
Because of $F_{interaction}(z)$, the resonance frequeny ω_R shifts to a new frequency ω'_R



F.J. Giessibl, Advances in atomic force microscopy, Rev. Mod. Physics, 75(3), 2003

FREQUENCY MODULATION MODE

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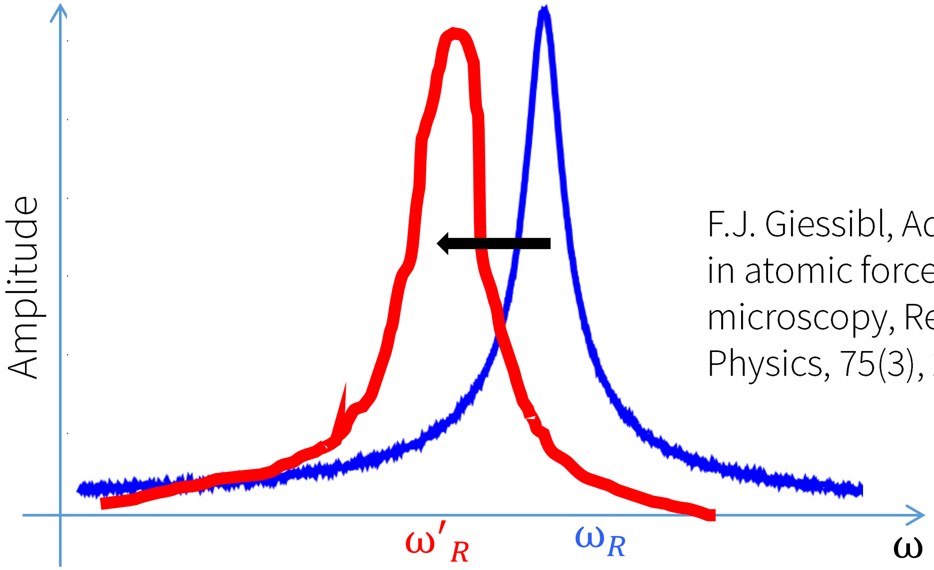
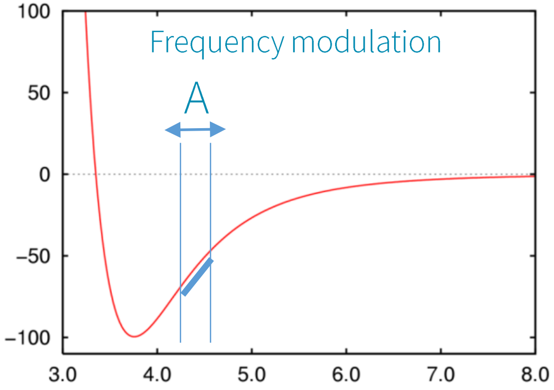


F.J. Giessibl, Advances in atomic force microscopy, Rev. Mod. Physics, 75(3), 2003

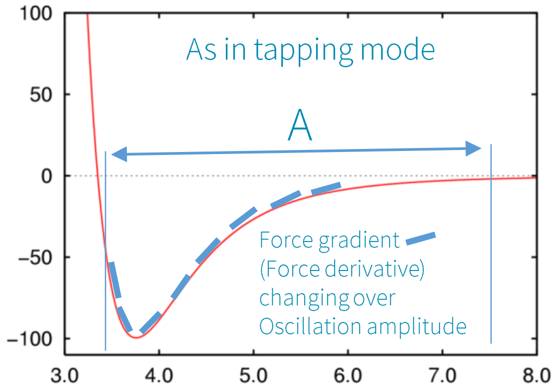
$$m\ddot{z} + \delta\dot{z} + kz = F_{interaction}(z) + F_{0(\omega t)}$$

can be rewritten if two conditions are fulfilled

1. If oscillation amplitude A explores a constant Force gradient over the oscillation, meaning



And not



2. If cantilever spring constant k is lower than the Force gradient k < d$\boldsymbol{F}_{interaction}$/dz

FREQUENCY MODULATION MODE

If the two conditions are fulfilled,

$$m\ddot{z} + \delta\dot{z} + kz = F_{interaction}(z) + F_0(\omega t)$$

We can use Taylor expansion for $\boldsymbol{F_{interaction}} = \boldsymbol{F_{int}}$ around its oscillation center Z0

$$m\ddot{z} + \delta\dot{z} + kz = F_{int}(z - z0) + \left(\frac{dF_{int}(z - z0)}{dz}\right)(z - z0) + \cdots + F_0(\omega t)$$

Where $\left(\frac{dF_{int}(z-z0)}{dz}\right)$ is the force gradient. Now it is the equation of a linear harmonic oscillator that can be solved analytically as we have done in absence of interaction force, leading to an harmonic solution equal to the one we obtained, except for the new resonance. We can indeed define a new resonance frequency $\boldsymbol{\omega'_R}$ that replaces $\boldsymbol{\omega_R}$

$$\omega'_R \approx \sqrt{\frac{k - \frac{dF_{int}}{dz}}{m}}$$

$$A = |z| = \frac{\frac{F_0}{m}}{\sqrt{(\omega_R{}^2 - \omega^2)^2 + \omega^2\delta^2}}$$

$$\text{Phase} = \arctan(\varphi) = \frac{\delta\omega}{\omega_R{}^2 - \omega^2}$$

FREQUENCY MODULATION MODE

Defining the frequency shift as df = $\omega'_R - \omega_R$

$$df = \sqrt{\frac{k - \frac{dF_{int}}{dz}}{m}} - \sqrt{\frac{k}{m}}$$

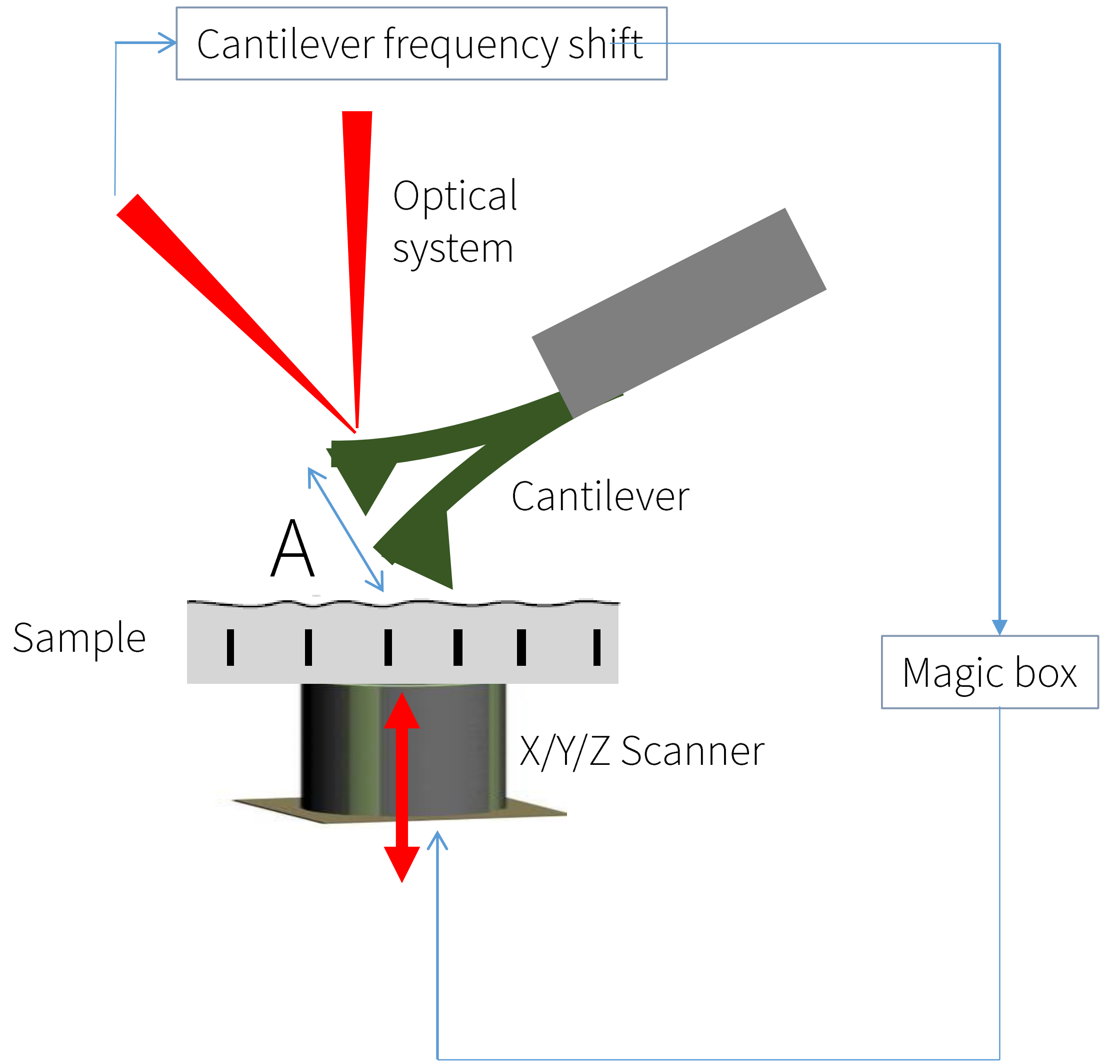
Using k < dF_{int} /dz, we can write $\sqrt{\frac{k - \frac{dF_{int}}{dz}}{m}}$ as $\approx \left(1 - \frac{\frac{dF_{int}}{dz}}{2k}\right)\sqrt{\frac{k}{m}}$

leading to $df = \left(1 - \frac{\frac{dF_{int}}{dz}}{2k}\right)\sqrt{\frac{k}{m}} - \sqrt{\frac{k}{m}} = -\frac{\frac{dF_{int}}{dz}}{2k}\sqrt{\frac{k}{m}} = -\frac{\frac{dF_{int}}{dz}}{2k}\omega_R$

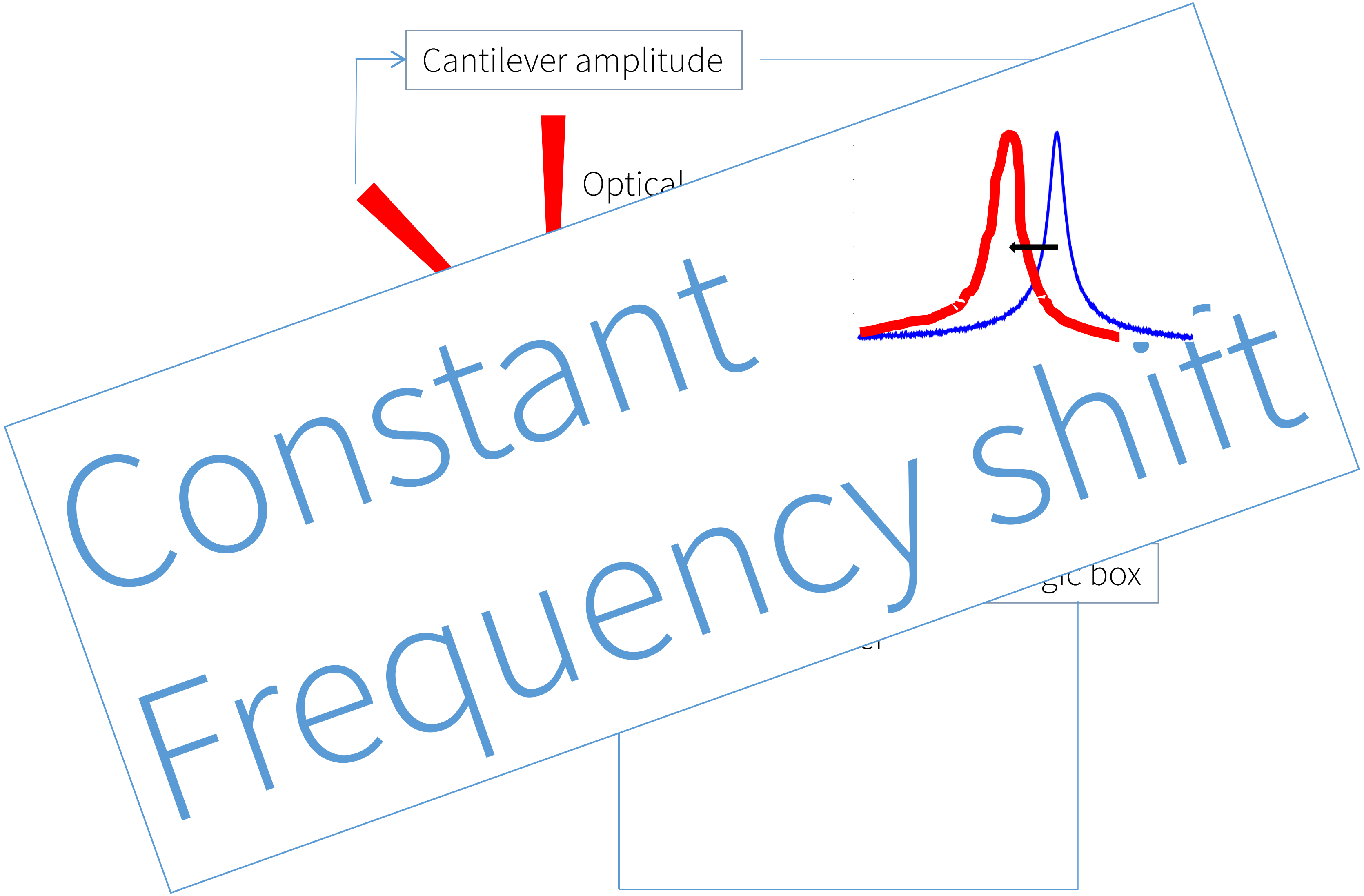
Which means that in frequency modulation mode,

the frequency shift is proportional to the tip-sample interaction force gradient $\frac{dF_{int}}{dz}$

AFM operational scheme



AFM operational scheme

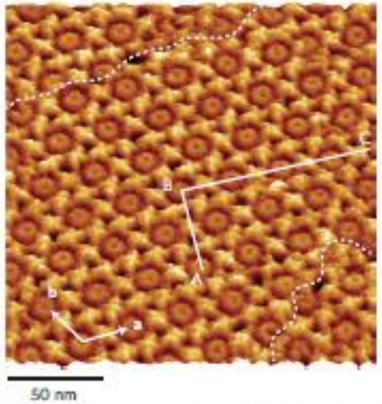


Frequency modulation mode

Mainly used for AFM in vacuum
High Q-factor is important

Bio (in liquid) application on FLAT samples

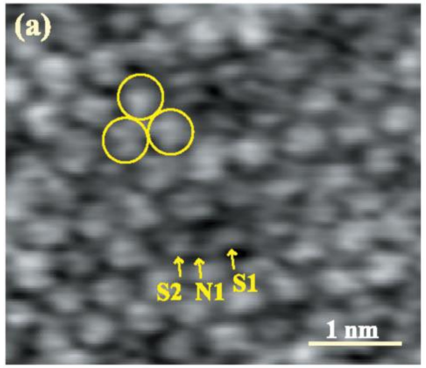
Hirofumi Yamada



Antibody crystal

S. Ido et al.
Nature Materials,
13, 264-270, 2014

Takeshi Fukuma



DPPC bilayer

T. Fukuma et al.
Physical Review Letters,
98(106101), 2007