

Micro Robotics

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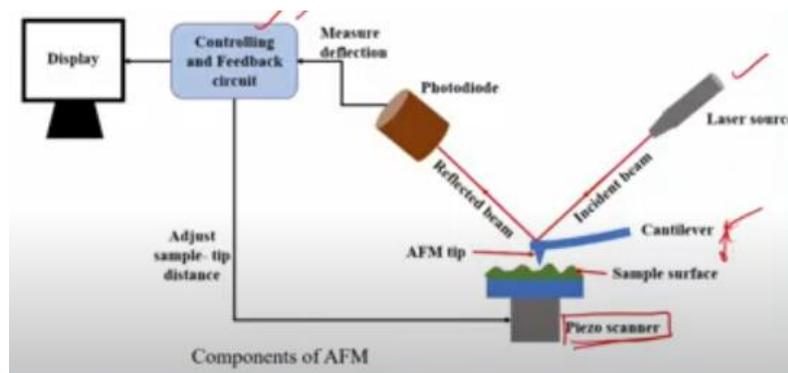
Week-9

Lecture-42

Microsystems for Microrobots (Manipulation) - Module 02

We had already discussed the overall propulsion mechanism, like the key aspect related to the propulsion mechanism. We discussed the varying modes of propulsion mechanisms in detail. Here we have shown a case study of an AFM, which is called an atomic force microscope. So, the main thing is the characterization tool for studying the surface characteristics or the surface behavior. So, like this tool is a kind of a micro and nano robot because of its functionality as well as because of its application. Let us take an example to see some of the key characteristics.

Here we will discuss in detail the overall mechanism which has been deployed with reference to the atomic force microscope. In the introductory slide the discussion on micro robots shows potential application in material characterization. Because of its micro manipulation it has a wide spectrum towards material characterization. Here, with reference to the atomic force microscopy, the manipulation behavior has a good impact.



So, with reference to the micro robotic related applications. Now we will discuss the key constructions of this atomic force microscope. When we closely observe the different components that are involved in it, the major component that contributes towards surface

integrity is the cantilever and then there is a laser source and a photodiode available. The light from the laser source is incident on the AFM, and it is reflected on a photodiode. The photodiode measures the reflection and a feedback circuit which connected to the display.

Now, in this system, we have a piezo scanner, the sample is placed over the piezo scanner, which requires a characterization. The main objective is to study the overall surface integrity or to study the overall surface waviness or the surface roughness. We have placed a sample surface and then a cantilever beam, which is AFMT So, the incident beam is on the cantilever, the cantilever beam is made to trace the profile of the sample surface. The waviness in the cantilever beam is continuously monitored using a reflected beam. The overall deviation that is happening on the sample surface is measured using a piezo scanner.

This piezo scanner will be helpful for measuring the overall waviness, as a piezo scanner is mainly meant for manipulating the sample based on the cantilever motion. So that is the reason. The overall motion of the cantilever beam is sensed and recorded using a photodiode, and the feedback gets two signals, so one is from the piezo sensor, and the other one is from the photodiode. Hence, both are getting an interface and appropriately the control strategies are being deployed into it. Now to look into the fundamentals of the atomic force, the cantilever is a micro-manipulating element.

Since the cantilever has a very narrow tip, in order of few nanometers. It has a kind of a contact and non-contact based micro manipulation. We will discuss in detail how these contact and non-contact based micro manipulations are efficiently participating towards the material characterization. For this, we need to understand the fundamentals with reference to the overall micro manipulation of this AFM tip. Now, when we try to look into the construction and working principle, we will discuss the overall cantilever with the atomic force microscope tip.

The cantilever is a micro machine beam which is ideally made out of a silicon or a silicon nitride. Its stiffness has to be much smaller than its spring constant for a better resolution. Now, the spring constant and the resonant frequency of the cantilever are represented as K , is depends upon the parameter E , which is the Young's modulus of the material. As, we are using a silicon nitride, the value for silicon nitride is 1.5×10^{11} Newton per meter square.

It also depends upon the length, width and thickness of the cantilever beam respectively. So the overall equation for measuring the spring constant and the resonant frequency is $K = \frac{E T^3 B}{4 L^3}$. So here the frequency is represented by $f = \frac{1}{2\pi} \sqrt{\frac{E B}{12 \rho L^3}}$. So ρ corresponds to the density of the cantilever

material.

- Cantilever is a micromachined beam made of silicon or silicon nitride.
- Its stiffness has to be much smaller than its spring constant for better resolution. Spring constant and resonant frequency of cantilever are;

$$k = \frac{Et^3b}{4l^3} \quad \text{and} \quad f = \frac{(1.8751)^2}{2\pi} \frac{t}{l^2} \sqrt{\frac{E}{12\rho}}$$

Where,

E is Young's modulus of material (for silicon nitride, $E = 1.5 \times 10^{11} \text{ Nm}^{-2}$).

l, b and t are length, width and thickness of the cantilever beam, respectively.

P is density of cantilever material.

- Since low value of stiffness is advantageous for measurement of soft materials, we aim to reach as low value as possible.
- While measuring in liquid environments, there is a fundamental limitation of lowering k.

Since a low value of stiffness is advantageous for the measurement of soft material, we need to reach a low value as possible. and then while measuring in the liquid environment there is a fundamental limitation in lowering the K. So these are some of the key challenges which need to be addressed. When we observe the cantilever with the AFM tip, the cantilever is in a thermodynamic equilibrium with a thermal bath at a temperature T and has a thermal energy that we can represent as KBT, Kb is the Boltzmann's constant.

Let us consider a 1-degree-of-freedom cantilever that has only a vertical motion and the thermal energy increases the elastic energy stored in the cantilever. So ideally when we try to equate the thermal energy and the overall thermodynamic equilibrium. So half k A square equals half k B T where when we try to calculate the A which is nothing but the A is the oscillation amplitude of the cantilever which is root of k B T by k. So these soft cantilevers are used in contact mode to avoid damage to the samples and stiff cantilevers are used in a dynamic mode for appropriate operations. Now when we try the calibration of this system, the mass of the cantilever is distributed uniformly throughout the length for

$$\frac{1}{2}kA^2 = \frac{1}{2}k_bT$$
$$A = \sqrt{\frac{k_bT}{k}}$$

Where,

A is oscillation amplitude of cantilever.

Soft cantilevers- Used in contact mode to avoid damage to samples.

Stiff cantilever- Used in dynamic modes.

calibration and its effective mass m_{naught} is considered. This method suggested by the researchers, is the change in the Resonant Frequency f of the cantilever as measured by a small addition of mass. So, $\omega^2 = k/m$

star plus m naught and f equals omega by 2 pi. So, for the accurate dimension of the cantilever, the spring constant is given by $K = 2b \pi L f^3 \rho^3 / E$. So L and B are the length and width of the cantilever, rho is the density of the material, E is the Young's modulus and F is the measure of the resonant frequency. Now, when we need to consider the overall dynamics of a cantilever in a liquid, the spring constants depend only on the material properties, but the viscosity of the surrounding medium affects the mechanical responses.

Atomic force microscope as micro/nano robot

1. Construction and Working

A) Cantilever with AFM Tip

Cantilever Calibration:

- The mass of cantilever is distributed uniformly throughout the length for calibration its effective mass (m_0) is considered.
- In a metho suggested by Cleveland and coworkers, the changes in resonant frequency (f) of the cantilever were measured as small additional masses m^* .

$$\omega^2 = \frac{k}{m^* + m_0} \quad \text{and} \quad f = \frac{\omega}{2\pi}$$

For accurate dimensions of the cantilever, the spring constant is given as

$$k = 2b(\pi L f)^3 \sqrt{\frac{\rho^3}{E}}$$

L and b are length and width od cantilever, ρ is density of material, E is Youngs modulus and f is measures resonant frequency.

So let us consider the cantilever is dipped in a liquid. and inside we have a waviness the liquid reduces the resonant frequency of the cantilever. So the movement of the cantilever driven by an externally oscillatory force $F(t)$ equals $F_0 \cos \omega t$ which is derived by the equation $m \frac{d^2 z}{dt^2} + k \frac{dz}{dt} + \gamma z = F_0 \cos \omega t$. So z is the vertical displacement of the cantilever M is the mass of the cantilever, F_0 is the amplitude of the oscillating force and γ is considered to be the damping coefficient. Then the overall governing equation is represented when we consider the cantilever working in a liquid medium.

- The spring constant depends only on material properties. But viscosity of surrounding medium affect the mechanical response.
- Let the cantilever be dipped in liquid,
- The liquid reduces the resonant frequency of cantilever. The movement of cantilever driven by external oscillatory force $F(t) = F_0 \cos(\omega t)$ is described by following equation,

$$m \frac{d^2 z}{dt^2} + k \frac{dz}{dt} + \gamma z = F_0 \cos(\omega t)$$

Where,

z is vertical displacement of cantilever; m is mass of cantilever; F_0 is amplitude of oscillating force; γ is the damping coefficient.

Gamma is $M\omega$ naught by Q so ω naught is the free vacuum resonant frequency and ω_r is the free vacuum free ω_r is the resonant frequency in fluid Q is the quality factor. so when we consider the gamma equals $M\omega$ naught by Q and ω_r equals ω naught root of $1 - \frac{1}{2Q^2}$. The solution of the differential equation is z equals $b e^{(-\alpha t)} \cos(\omega t) + \beta + a \cos(\omega t + \varphi)$. After time t equals 1 by $\alpha 2q$ by ω_0 , the transient term diminishes and the motion tip is dominated by a steady-state term. And the amplitude A , ω , and the phase lag φ can be calculated by the equation A , ω equals f naught by m ω , that is the square root of ω naught squared minus ω squared, all squared plus ω ω naught by q squared, and the $\tan \varphi$ is represented as ω ω naught by q and ω naught squared minus ω squared.

Here,

$$\gamma = \frac{m\omega_0}{Q} \text{ and } \omega_r = \omega_0 \sqrt{1 - \frac{1}{2Q^2}}$$

ω_0 is free vacuum resonant frequency, ω_r is resonant frequency in fluid, Q is quality factor.

The solution of the differential equation is,

$$z = B \exp(-\alpha t) \cos(\omega_r t + \beta) + A \cos(\omega t + \varphi)$$

After time $t = 1/\alpha = 2Q/\omega_0$, the transient term diminishes and motion of tip is dominated by steady term only. Amplitudes ($A(\omega)$) and phase lag (φ) can be calculated by following equations:

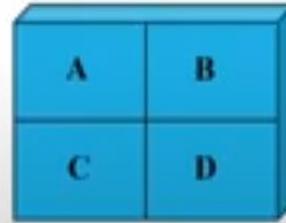
$$A(\omega) = \frac{F_0/m}{\sqrt{(\omega_0^2 - \omega^2)^2 + \left(\frac{\omega\omega_0}{Q}\right)^2}} \quad \text{and} \quad \tan \varphi = \frac{\omega\omega_0/Q}{\omega_0^2 - \omega^2}$$

Now, let us discuss in detail this construction: we have a photodiode, how the photodiode participates, and what kind of impact it has on the system. So, these photodiodes are the detectors that measure the deflection of the reflected beam from the cantilever. It provides the data for the position of the cantilever with respect to its original position. These photodiodes are made up of 4 quadrants. So let us consider measuring the least spot portion overall as well as the direction.

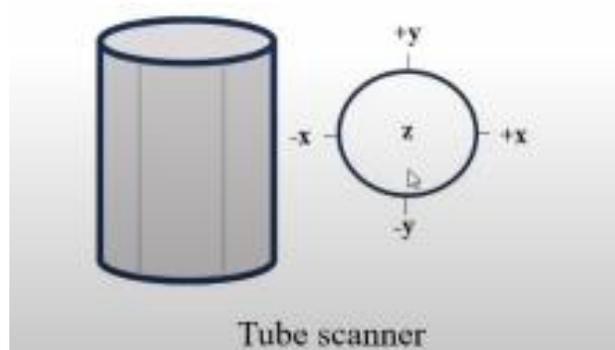
These are the four quadrants of the photodiode. So, when we consider a vertical deflection by comparing the signals from the top and bottom halves of the detector, it is meant for measuring the interaction force, and then there is a lateral twisting that exists. So, this lateral twisting is used for comparing the signals from the left and right halves. So, when we consider the vertical diffraction signals, we can write A plus B minus C plus D as a ratio of A plus B plus C plus D . So, ideally, this will act as a mechanism to investigate the overall reflected signal that is coming out of the cantilever.

g the signals from left and right halves.

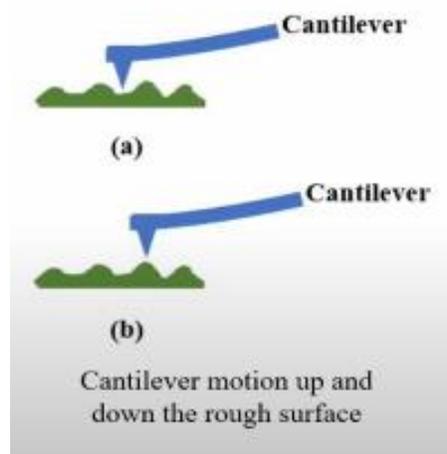
$$\text{Vertical Deflection signal} = \frac{(A+B)-(C+D)}{(A+B)+(C+D)}$$



Now let us discuss the piezo scanners. We have already discussed these piezo scanners. So these piezo scanners are a type of piezoelectric transducer, which is used for accurately positioning the tip of the sample with sub-nanometer precision. So they are highly sensitive, stable and reliable. The application of external voltage induces a reverse piezoelectric effect in the scanner which results in change in its dimension.

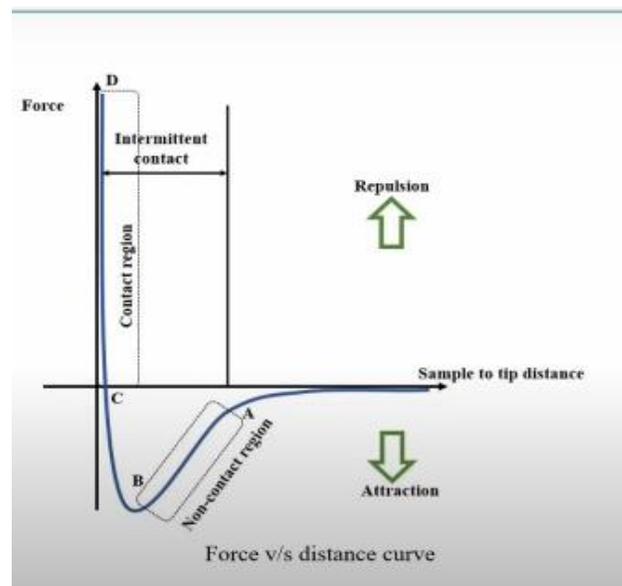


Generally, these kinds of AFM-related applications involve tube scanners, which are stacked piezoelectric structures. So ideally, we have a manipulation in the Z direction, X direction, and a manipulation in the Y direction. Appropriately, the samples are mounted, and the overall manipulation of the samples will have an impact on the structure. Now, let



us discuss the different principles that are being deployed with reference to this cantilever perspective. So in a cantilever, it is made to trace the profile, and accordingly, we get a signal out of it. So there are two different mechanisms that exhibit two different kinds of modes: one mode is a motion up, and the other one is a motion down along the surface roughness. Hence, when the cantilever is moving along the waviness, we will get a deflection from this. So the waviness that the cantilever is tracing will be efficiently recorded by the photodiode. So the scanning of the sample surface with the sharp tip or probe, known as a cantilever, basically depends on the force between the tip and the sample surface. So, when the AFM tip is in close proximity to the sample surface, the force between the tip and the sample surface leads to the deflection of the cantilever governed by Hooke's law.

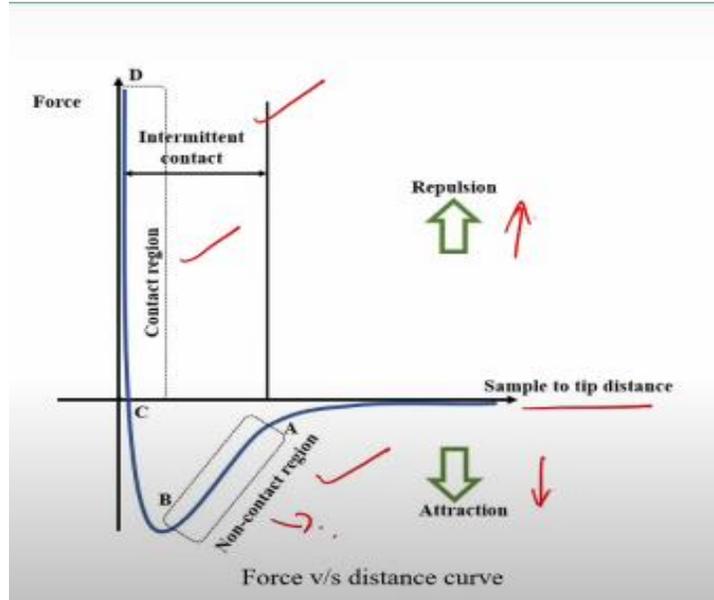
So, the motion of the cantilever is captured and amplified to generate an image of the surface. The AFM works in two different modes. One is force mode, and the other is distance curve mode. So, let us discuss the force and distance curve modes. Now we will try to plot a graph with reference to this force mode versus the distance curve mode.



In force mode, if I try to plot a graph with reference to the force and the sample, there are four different regions known as intermittent contact, contact region, non-contact region, and the sample-to-tip distance. So the plot is between force and sample tip distance. So we have two different domains: one is a repulsion domain, and the other is an attraction domain. So when the sample-to-tip distance is high, that is in the region beyond point A, no interaction happens between the sample and the tip. However, when the distance is reduced and it comes into the range of A and B, which is called the non-contact region.

Due to a greater distance, the attractive forces are dominant between the tip and surface, and this region is called a non-contact AFM. If the distance is in the region of C and D, the

repulsive force is dominant, and the region is used for a contact-based AFM. So both regions will be utilized for intermittent mode, which we can call tapping mode. Both the contact region and the non-contact region will be utilized when the AFM is in tapping mode. Now let's discuss some of the key principles.

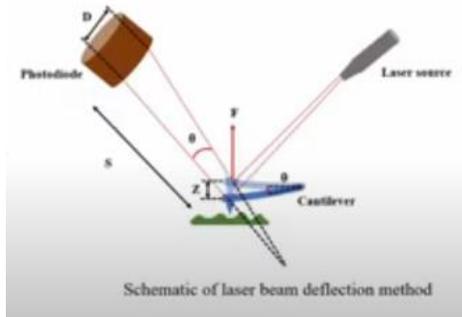


Now let us consider a tip motion. When a tip is approaching, the distance from the tip to the surface is in the range of 10 to 100 microns, and the overall distance is reduced to a few microns. When it is close to the surface, the distance is on the order of nanometers to atomic distances. Besides, there is no interaction that occurs there. When the tip approaches, there is going to be a repulsion, which is an electrostatic force. When the tip is closer to the surface, basically in the order of nanometers to atomic distances, the repulsion that results from Van der Waals force, capillary force, chemical potential, and magnetic force is exhibited.

Now, with reference to the contact, there is going to be a tip touching sample, and then from an interaction perspective point of view, a material stiffness and a viscoelastic response are exhibited. Now let us talk about the tip-retracting phenomenon. In the case of a tip retracting phenomenon, the tip is in contact with the surface. In the tip retracting phenomenon, there is going to be a waviness that exists because of the movement. There are three different motions that can be monitored: one is lifting off from a few atomic distances to nanometers; second, the tip moves further away, which is in the order of nanometers; and third, the tip moves far from the surface, which is in the order of 1 to 5 microns.

Now, during the liftoff, when a few atomic distances to nanometers are present, adhesion occurs, resulting in chemical affinity, surface coating, and cell surface interaction. Now,

with respect to a tip farther away by a few nanometers, adhesion takes place, resulting in stiffness and a structural transition, which is exhibited. When the tip is far from the surface, not much interaction is observed. So when we try to look into the overall force detection method through an example of the laser beam deflection method. In the laser beam deflection method, a cantilever is used where the moment of the cantilever is marked as Z , and a photodiode and a laser source are used.



The force exerted is marked as F , and then a laser is made to interact with the cantilever. So when it is in position A or B, it will receive a reflected signal. Consider that the AFM tip is moved away from the sample by a distance z in a vertical direction. This is due to the repulsive vertical force F between the sample and the tip. So the reflected laser beam from the cantilever is deflected by an angle θ . So the angle at the end of the cantilever in the presence of force F is recorded as $\theta = \frac{FL^2}{2EI}$, where E is considered to be the Young's modulus and I is considered to be the moment of inertia. So this is a kind of laser beam deflection method. Now, when we want to measure the force deduction method for imaging, with reference to the laser beam deflection method for a rectangular cantilever, let us consider E and I , which are equal to $\frac{KL^3}{3}$. So K is a spring constant fulfilling L in the cantilever length, which can be represented as $F = Kz$. For a small displacement of the tip.

Therefore, the amplitude displacement of the cantilever is D . So the accuracy of the beam deflection method can be as high as 0.1 Armstrong, and it is limited to random thermal excitation of the cantilever. Let us consider a kind of piezoelectric cantilever and a tuning fork. In this particular case, we have a piezo scanner and a sample where the piezoelectric layer acts as a kind of piezoelectric cantilever, and then there is an AC driving signal being fed here.

Atomic force microscope as micro/nano robot

Force Detection Methods for Imaging:

1. Laser Beam deflection method

For rectangular cantilever,

Where, k is spring constant fulfilling
 l is the cantilever length.

Thus,

$$EI = \frac{kl^3}{3}$$

$$F = kz.$$

$$\theta = \frac{3z}{2l}$$

For small displacements of the tip,

$$\tan \theta \approx \theta = \frac{D}{S}$$

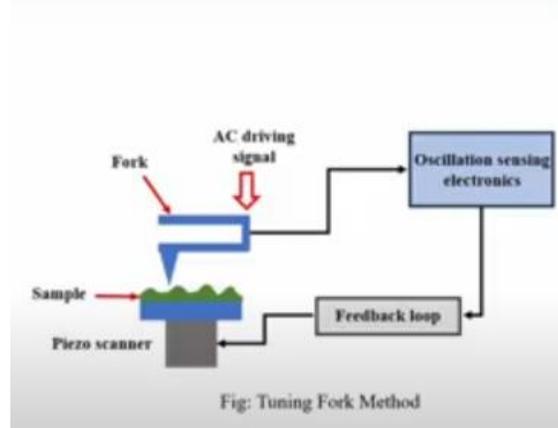
Thus, the amplified displacement of the cantilever is

$$D = \frac{3Sz}{2l}$$

The accuracy of beam deflection method can be as high as 0.1 Å. It is limited by random thermal excitation of the cantilever.

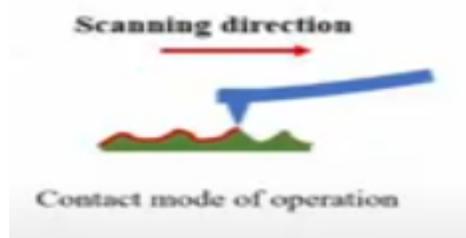
So, the deflection from the piezo layer is measured by the deflection sensing electronics, and a feedback loop exists. From this feedback loop, the feedback is fed into the piezo scanner. So, that is based on the deflection of these piezo layers. Appropriately, a signal is fed into the piezo scanner, and the movement of the piezo scanner is monitored. The piezoelectric thin film is coated onto the cantilever beam. Bending of the cantilever beam stresses and deforms the piezoelectric layer. So, due to a direct piezoelectric effect, a voltage is generated in the piezoelectric layer with an amplifier circuit, which can obtain a voltage proportional to the cantilever deflection. So, this piezoelectric layer is also useful in providing oscillation to the cantilever by applying an external AC field to it through an AC driving signal. Through this AC driving signal, a mode is exhibited and the piezoelectric thin film moves appropriately. Now we have a kind of tuning fork; the AFM tip is glued to one end of a small quartz tuning fork.

The force oscillates the tuning fork and then causes damping. So when we try to look into the overall configuration, the fork is integrated with a cantilever. Then there is a small AC driving signal and an oscillator with sensing electronics and a feedback loop in place. The feedback loop is connected to the piezo scanner, which scans the sample.



So this method is called the tuning fork method. So when there is a deflection in the cantilever, the fork is going to exert a kind of force to oscillate. So the damping of the amplitude of oscillation due to tip-sample interaction is monitored. The force resolution is generally on the order of 0.1. So the probe does not touch the sample employed for this non-contact-based AF.

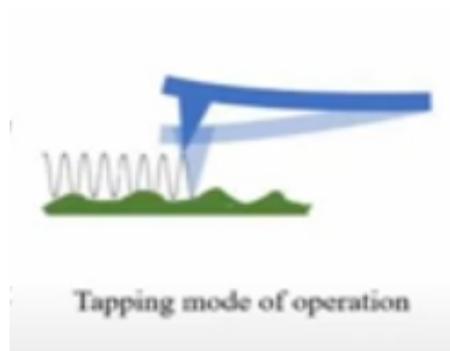
So here, the overall feedback is monitored from the piezo scanner as well as the sample. Now let us discuss the two different modes of operation, one of which is called contact mode. In contact mode, the tip never leaves the surface. It is used for very high-resolution imaging. For example, you have a sample, and the tip will try to move or trace the sample; hence, we can continuously see the waviness in the system.



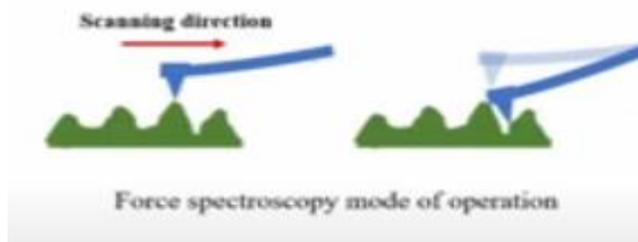
There is a maximum vertical force that is used to minimize the compression of the sample. Fast scanning is good for measuring the roughness of the surface. In the case of a soft sample, it may damage the sample; hence, measurement can be done in air. So, this is one of the major limitations that are being deployed in the case of a contact mode.

Sometimes the lateral force may also distort the image. So, this is an important aspect that we may need to look into. The next mode is called tapping mode. In this case, the tip is not in contact with the surface for most of the oscillation cycle. It is used for imaging samples

that are not firmly struck on the surface, such as molecules. So the cantilever is driven close to the resonance of the system to provide an amplitude for oscillation.



The cantilever oscillates, and the tips make a repulsive contact with the surface at the lowest point of the oscillation. So, the oscillation can be achieved with a small piezo element in a cantilever holder and an AC magnetic field, or a piezoelectric cantilever, or periodic heating with a laser beam. So, these are some of the kinds of modes or oscillations that can be achieved where the imaging forces are lower. This is one configuration with reference to the tapping mode. Besides, when we talk about this FM AFM, it is a kind of force modulation mode.



So the tip does not leave the surface but makes a small oscillation. This dynamic form of contact mode is called force modulation, where the cantilever is kept oscillating within a fixed amplitude at its resonant frequency. The image is formed by the constant frequency shift between the current frequency and the free resonant frequency. So we will discuss this non-contact mode and the other feedback-related modes in the upcoming classes.