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Compensation of Parasitic Capacitance of Quartz Tuning Fork in AFM

Yidai Liu

Physics Department, Hong Kong University of Science and Technology, Hong Kong, China
Email: liuyidai518@163.com

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Abstract

We have built an atomic force microscope using a quartz tuning fork as sensor. The excitation method we adopted, the electrical excitation, introduces stray capacitance into the signal-processing circuit. In this report, we demonstrated a simple but effective method to compensate for this parasitic capacitance by adding a compensator circuit consisting of an inverting amplifier and a capacitor. The capacitor is connected in series with the inverting amplifier and the compensator is connected in parallel with the quartz tuning fork. The resonance curve of the system measured after adding the home-made compensator resembles that of a pure RLC circuit, meaning that the stray capacitance is successfully eliminated. Furthermore, we tried to use our equipment to measure PDMS sample and got clean data. This system can be further combined with confocal microscope and diamond with NV defect to build scanning NV magnetometry.

Keywords

Atomic Force Microscope, Quartz Tuning Fork, Stray Capacitance, Compensator Circuit, PDMS Sample

1. Introduction

Quartz tuning fork has been used as the sensing component of atomic force microscopes (AFM) for various reasons. They are small in size, having low damping effect, and very versatile [1] [2] [3] [4]. Many variations of this design exist including combining the tuning fork with a diamond with NV center to probe the magnetic field in the vicinity of the sample surface [5]. The biggest advantage of using quartz is its piezo-electric property which integrates easily into electric circuits and allows data to be obtained electrically [4] [6].

To use the tuning fork to measure atomic forces, we need to make it oscillate.

Although there always exists thermal excitation of the quartz tuning fork, the intensity is too small to be useful. There are mainly two ways to drive the oscillation of the fork, namely electrical excitation, and mechanical excitation. In a mechanical-excitation design, the input current drives a piezoelectric actuator attached to the fork which then drives the fork, while in an electrical-excitation design, voltage is applied directly to the quartz tuning fork. The material will deform according to the voltage applied. It is clear to us that the latter is simpler because it does not need an actuator. However, for the electrical-excitation design, the outcome is not so desirable because of stray capacitance intrinsic to the tuning fork and its wiring. There have been many ways to cope with this issue, including a theoretical approach [7], usage of tunable compensation circuit [6], and using another identical but immobilized tuning fork for compensation [4].

In this report, we designed a phase compensator consisting of a tunable inverting operational amplifier connected in series with a capacitor to try to eliminate the non-harmonic effects of the quartz tuning fork. We achieved a more compact design by using the op-amp chip instead of the transformer as introduced by Grober [8]. In addition to that, we tested our equipment by measuring the resonance frequency shift when the sensor is in contact with Polydimethylsiloxane (PDMS) sample.

2. Methods

2.1. qPlus Sensor

As shown in **Figure 1(a)**, the quartz tuning fork has two branches. They might oscillate symmetrically or asymmetrically, adding complexity to the measurement,

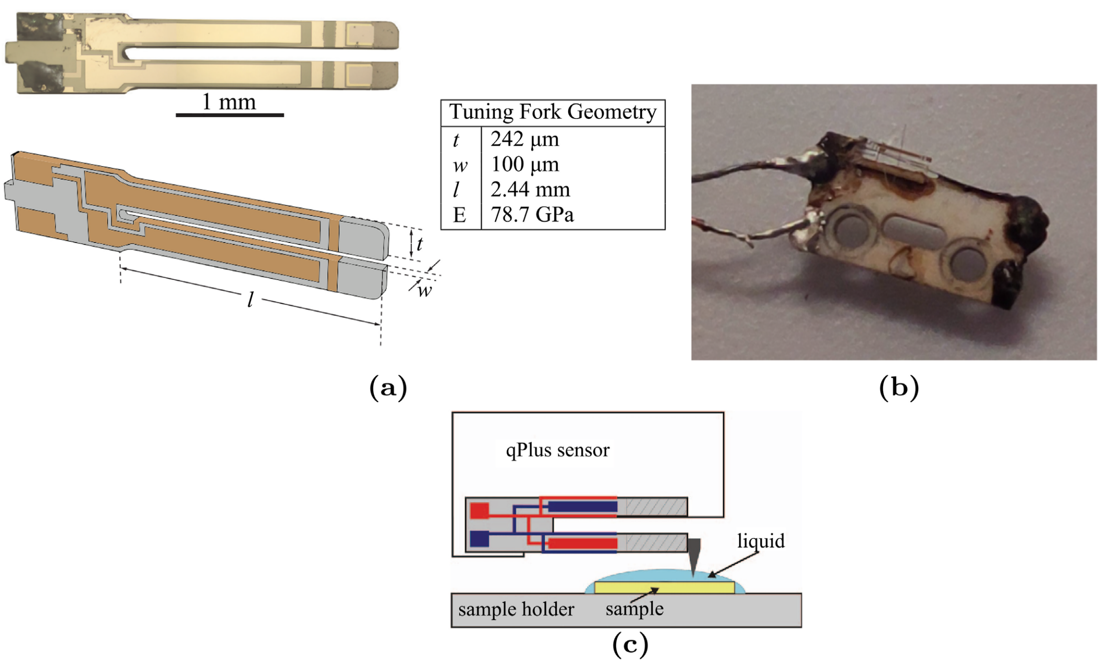

Figure 1. (a) A picture of the quartz tuning fork [6]. (b) A photo of the qPlus sensor. (c) Schematic arrangement of sensor and sample [10].

especially when the tuning fork becomes asymmetric when a tip is added to one of the branches to make a probe microscope. To maintain the symmetry of the tuning fork, balancing mass should be added to the other branch, which is obviously very difficult job. Alternatively, one can fix one of the branches to a firm base to make it a single quartz beam. This is called the qPlus sensor, which was first introduced by by Giessbl in 1998 [9].

In the setup of this report, we use the qPlus sensor with a tip on the moving beam, as shown in Figure 1(b) and Figure 1(c).

2.2. The Parasitic Capacitance

There are two ways to excite the quartz tuning fork, the mechanical way, and the electrical way, as illustrated in Figure 2. In the setup of this report, we used the electrical excitation method. According to the theorem proved by Butterworth [11], the tuning fork is equivalent to an inductor, a capacitor, and a resister connected in series, which is stunted by another capacitor [12], as shown in Figure 3.

This is essentially due to the fact that the effective force exerted on the two

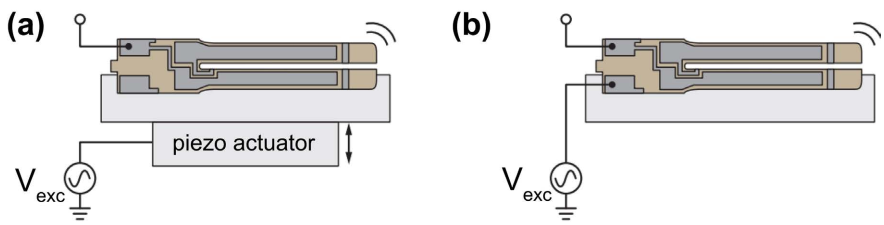

Figure 2. The two excitation methods: (a) mechanical excitation wherein the tuning fork is excited via the vibrations of its base driven by an actuator and (b) electrical excitation using an ac signal applied directly to one electrode of the tuning fork [6].

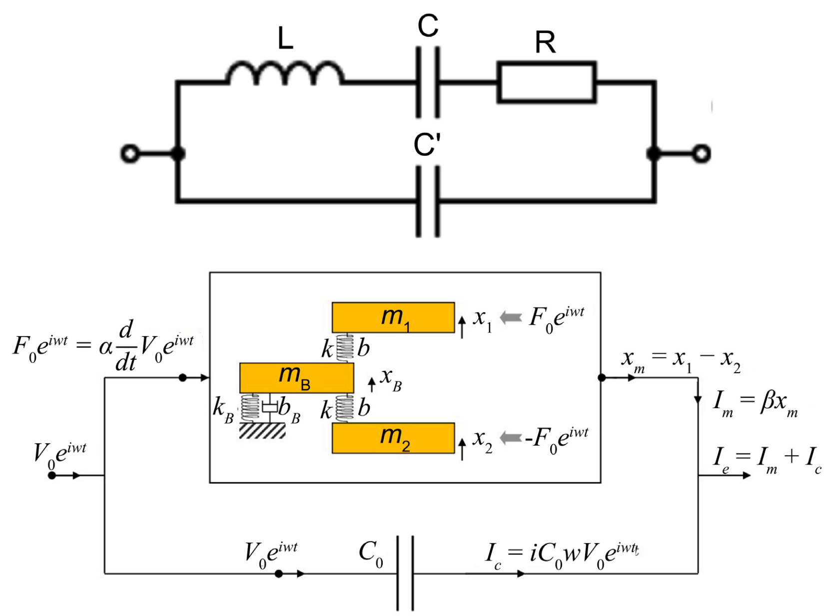

Figure 3. The equivalent circuit of the piezo-electric tuning fork [12].

prongs of the quartz tuning fork is proportional to the derivative of the applied voltage. And the resulting current is proportional to the relative displacement between the two prongs. The input voltage gets converted to force which drives the mechanical oscillation of the sensor. And the mechanical oscillation in turn alters the output current. So, both the actuation and detection are done electrically. The two factors α and β shown in **Figure 3** are the conversion factors that determines the relation between electrical signal and mechanical signal [12].

Without the stray capacitance, the quartz tuning fork or qPlus sensor is supposed to work like a harmonic oscillator which shows one single resonance peak in the resonance curve and a shift of the phase before and after the resonance frequency. For clarity and simplicity, here before resonance means the driving frequency is smaller than the resonance frequency of the harmonic part and vice versa. The parasitic capacitor alone has constant amplitude and phase given a stable ac input. When we add these two effects together to get the total output current, before the resonance frequency, the harmonic part and the stray capacitance part have same phase, thus they interfere constructively. But after resonance, the phase of the harmonic part changes and they start to have opposite phase, thus they interfere destructively, resulting in a local minimum right after the main resonance peak. This superposition is illustrated clearly in **Figure 4**.

The resonance behavior of the qPlus sensor is tested and the result is as shown in **Figure 5**. We can see a dip of the amplitude after the resonance peak due to destructive interference and the phase going back to the initial value after a brief drop at the resonance point instead of staying in the opposite phase.

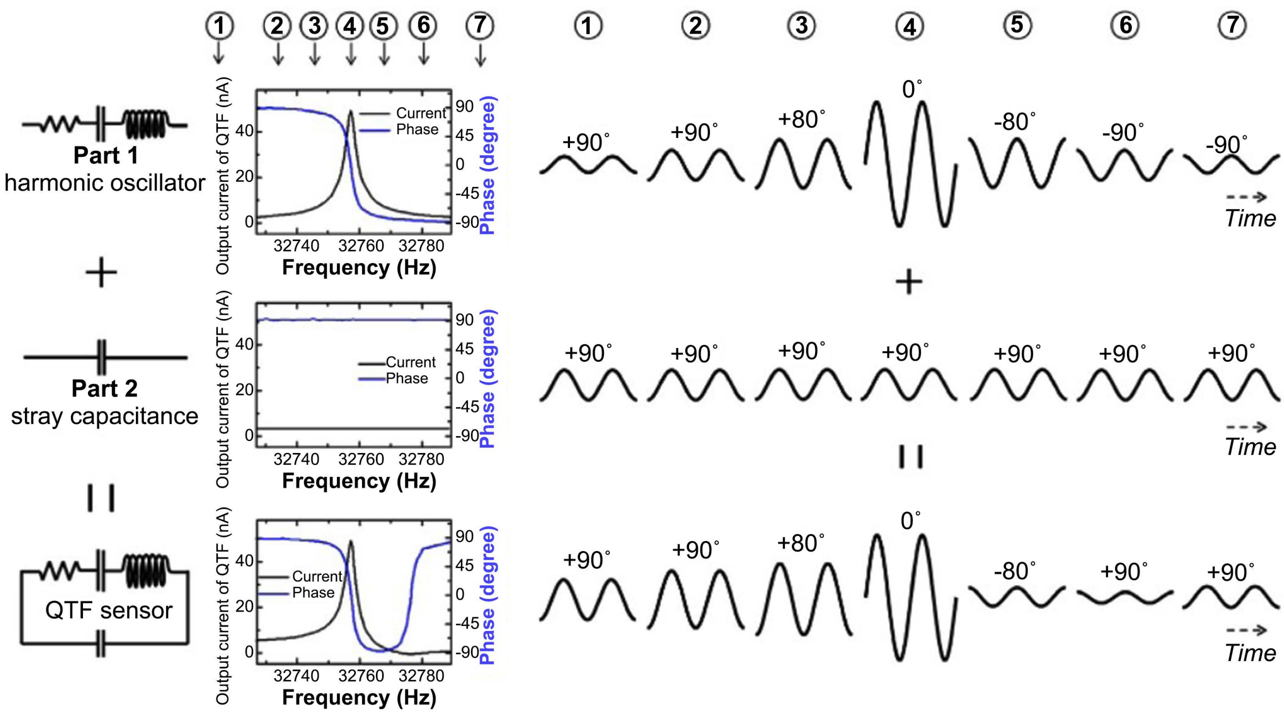

Figure 4. The resonance curve of the RLC (Part 1), stray capacitance (Part 2), and their superposition [4].

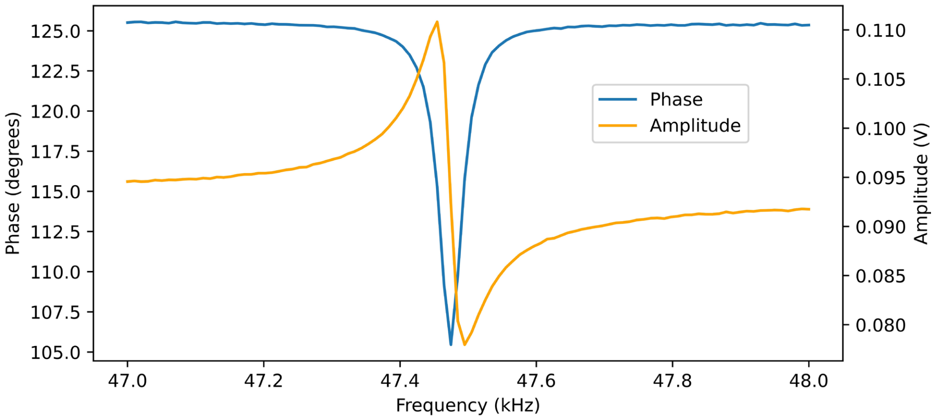

Figure 5. The measured resonance curve of the sensor without compensation with frequency scanning from 47 kHz to 48 kHz.

2.3. The Compensator

We dynamically measure the resonance frequency shift in real time while probing by keeping track of the zero phase on the phase curve using the PID feedback control loop, using frequency as the control variable and zero phase as the desired setpoint. The frequency is dynamically modulated based on the error which is the difference between the measured process value and the desired setpoint. PID controllers work best when the loop to be controlled is linear and symmetric. So, we need to compensate for the stray capacitance to get a phase curve which is roughly linear around the resonance point.

In order to compensate for the stray capacitance, we designed a compensator as shown in Figure 6.

The compensator is connected in parallel with the tuning fork, they share the same input voltage, and their current adds up. The op-amp in the compensator inverts the phase of the input signal (shifts by 180 degrees) and also amplifies it. The current then passes through the capacitor. Because the input signal of the capacitor in the compensator has inverted phase compared to the input signal of the tuning fork, the current from the branch of the compensator is supposed to interfere destructively with the current from the parasitic capacitor in the tuning fork when the current of the two branches add up. The gain of the op-amp is tunable by adjusting the two variable resisters. By fine-tuning the gain, we can make the amplitude of the compensating current to be the same as the stray capacitor current to achieve complete cancelation of the stray capacitance effect.

The operational amplifier we used is the ADA4899-1 chip manufactured by Analog Devices, which is unity-gain stable, having ultra-low distortion, and high speed [13] [14]. After fine tuning the gain, we get the compensated resonance curve of the sensor as shown in Figure 7.

We can see that after adding the compensator, the amplitude peak becomes more symmetric, and the phase goes from positive to negative after the resonance point, similar to that of a Lorentzian oscillator with minimal inharmonic behavior, which means that the stray capacitance is well compensated.

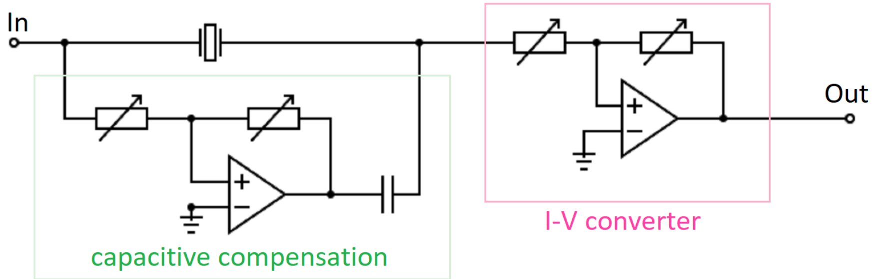

Figure 6. A simplified schematic of the compensator consisting of an inverting amplifier and a capacitor.

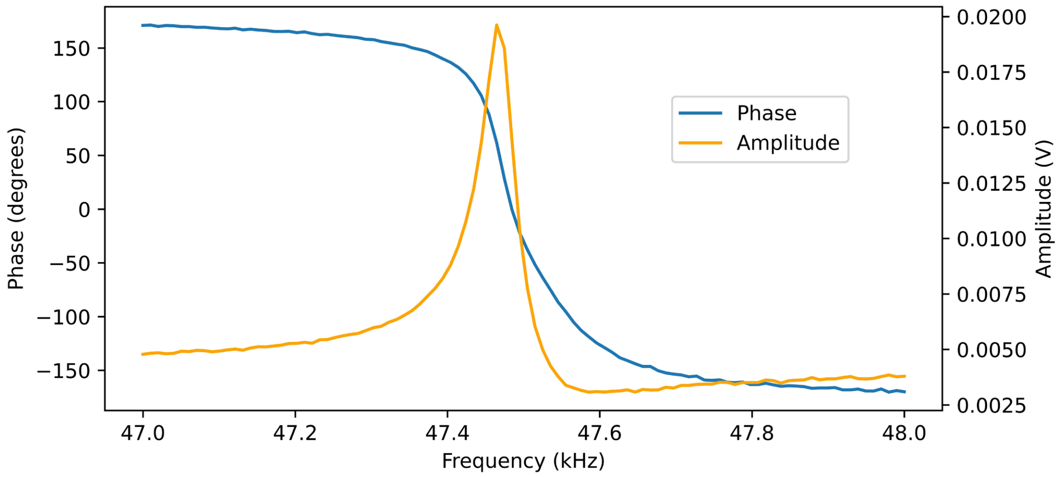

Figure 7. The compensated resonance curve after tuning the gain of the compensator with frequency scanning from 47 kHz to 48 kHz.

3. Results and Discussions

Polydimethylsiloxane (PDMS), whose chemical structure is as shown in **Figure 8**, is widely used as lubricants, damping fluids, and defoaming agents. Thus, its mechanical properties such as viscosity and surface tension need to be studied. Using the proposed system, we can measure various mechanical properties of the PDMS sample. However, in this report, we only used the sample to test the experimental setup.

We used a piezo-electric component to move the position of the sensor tip with precision, the larger the applied voltage (offset), the closer the tip is to the sample. We used the methods mentioned in the previous section to electrically actuate the quartz tuning fork with ac signal and modulated the driving frequency using PID feedback control loop to measure the shift of resonance frequency as the offset changes. The arrangement of the sample and sensor is as illustrated in **Figure 1(c)** on page 1. The full setup of the signal processing circuit is as shown in **Figure 9**.

We first let the tip of the sensor approach the sample. After the tip touches the surface of the liquid sample, the liquid wets the tip. So, later when we retract the tip from the liquid, liquid meniscus will form, and the tip does not break off from

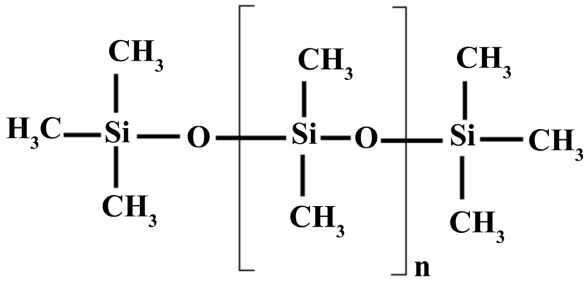

Figure 8. The chemical structure of Polydimethylsiloxane (PDMS) [15].

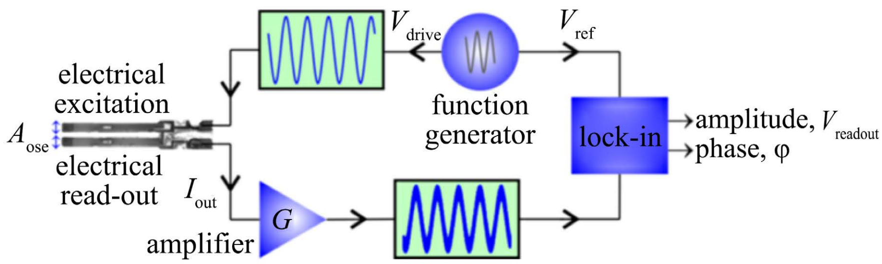

Figure 9. A schematic of the electronics signal processing part. A function generator generates ac driving voltage which is applied on the tuning fork and also used as reference signal for the lock-in amplifier. The current output from the tuning fork is amplified and sent to the lock-in amplifier to get the amplitude and phase information.

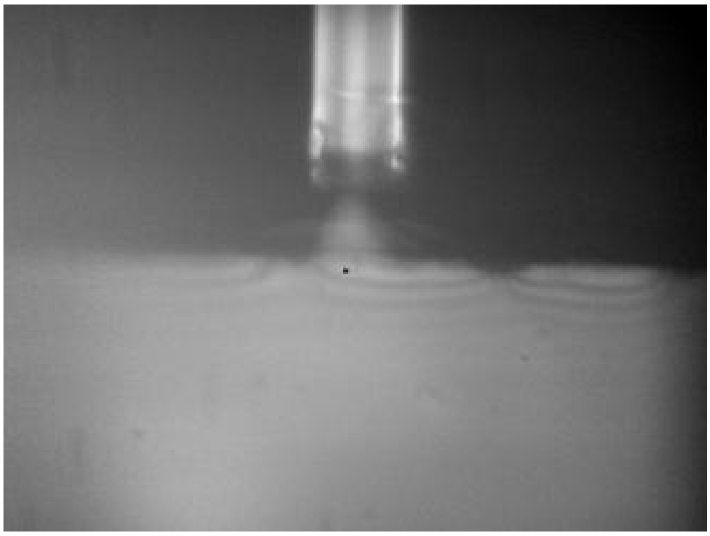

Figure 10. A microscopic picture of the liquid meniscus of the PDMS sample formed between the tip and the sample holder.

the liquid sample until the tip is pulled to a place much higher than the initial contacting point.

Figure 10 shows a microscopic photo of the PDMS sample hanging on the sensor tip just before rupture happens.

The frequency shift and amplitude change in a retracting process is recorded as in Figure 11. After rupture happens, the tip breaks free and has less damping effect, thus the oscillating amplitude increases, and the frequency shift decreases.

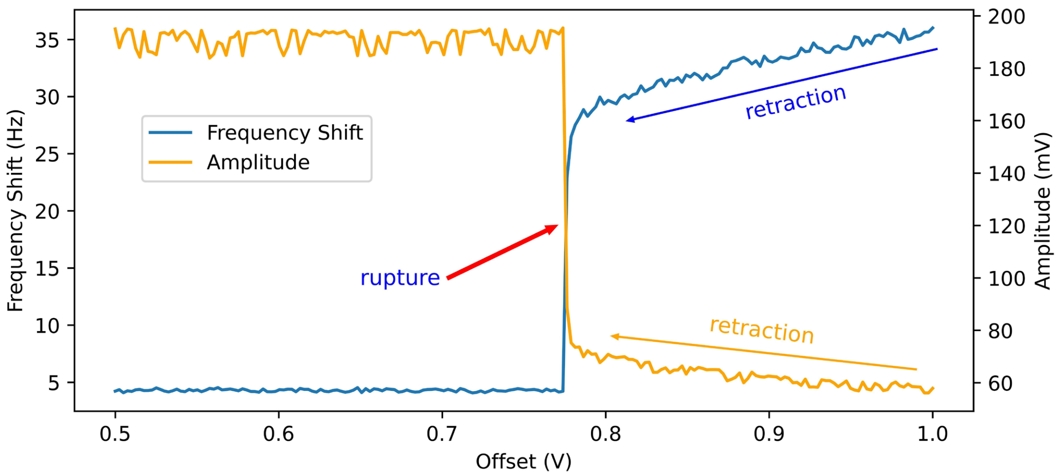

Figure 11. The frequency shift and amplitude change in a retracting process. Behavior before and after rupture is shown.

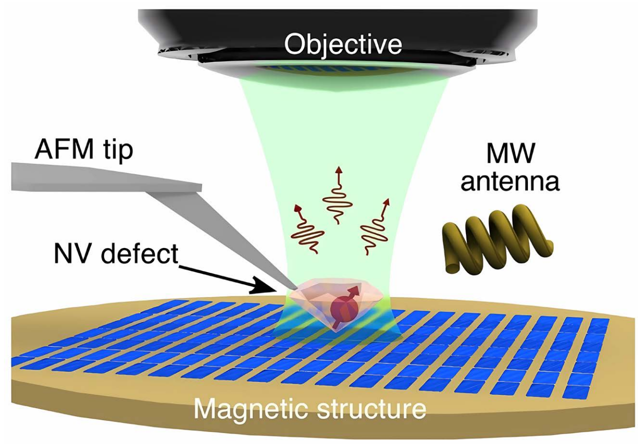

Figure 12. Simplified scheme of the scanning probe magnetometer combining a tuning fork based AFM and a confocal microscope. The tuning fork tip is functionalized with a single NV center. The confocal microscope is equipped with a microwave antenna to optically read out the NV center ESR transition. Retrieved from [16].

4. Conclusions

We have shown that the stray capacitance compensating system featuring inverting amplifier can effectively remove inharmonic effects of the sensor. The quartz tuning fork works as a force gradient sensor, allowing measurement of various mechanical properties of various types of samples. This simple but robust method may contribute to improve several electric-field induced mechanical systems (sensors, actuators, or resonator) by removing the unwilling non-linear effect of stray capacitance [4]. Furthermore, the tuning fork based AFM can be combined with confocal microscopy and diamond with nitrogen-vacancy (NV) defect to build scanning nano-magnetometry [5], see **Figure 12**. In this design, the AFM helps keeping the distance between the NV magnetic sensor and the sample by sensing the atomic forces, allowing controlled close proximity between the NV center and the sample.

However, there are some limitations of this method. Firstly, the compensator circuit may introduce additional noise into the system, which could affect the accuracy of the measurements. Secondly, the effectiveness of the compensator circuit may depend on the specific parameters of the system, such as the frequency range of the measurement and the magnitude of the stray capacitance. Also, the method may not be suitable for all types of atomic force microscopy applications, as the effectiveness of the compensator circuit may vary depending on the specific requirements of the measurement.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A: Experimental Setup

The op-amp chip used in this experiment was ADA4899-1 high speed op amp. The capacitor used was 1pF. The signal was processed using Zurich Instrument MFLI lock-in amplifier.