Active Q Control of an AFM Micro Cantilever Using PPF Controller

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Abstract: **The image excellence and resolution of the Atomic Force Microscope (AFM) functioning in tapping method is reliant on the quality (Q) factor of the detecting microcantilever. Decreasing the cantilever quality (Q) factor in the atomic force microscope (AFM), when functioning in tapping method permits for an increase in imaging speed. Though, this system uses a passive electrical impedance to modify the mechanical dynamics of the cantilever, which limits the amount of Q factor reduction possible. This paper describes that additional decrease in the cantilever Q factor may be found with the use of an active impedance in the piezoelectric shunt control method. The active impedance factors are considered in such a way that the piezoelectric shunt controller imitates a positive position feedback controller in a displacement feedback control loop. A significant decrease in cantilever Q factor is achieved using an active impedance compared with that realized with a passive impedance.**

Keywords: **Atomic Force Microscopy (AFM), micro cantilever, piezoelectric shunts control, tapping mode, Positive Position Feedback.**

1.   INTRODUCTION

The Atomic Force Microscope (AFM) [1] is one of the primary instruments for high resolution imaging of samples with nanoscale features. Tapping method [2] [3] is the most predominant AFM imaging method, as sample damage and distortion are greatly reduced compared with different methods of operation. While imaging in tapping mode, the sample is cross-examined by lightly tapping the surface with a sharp probe tip, which is located on the base of a microcantilever. The probe tip is oscillated at, or close to the cantilever's first resonance frequency while the sample is scanned below the cantilever, typically in a raster shape, using a piezoelectric scanner.

Positive Position Feedback (PPF) [4] is an operative vibration control method for smart actuators. Positive Position feedback makes use of comprehensive displacement measurements to achieve vibration suppression. Numerous features of Positive Position Feedback make it attractive for large space structure vibration atmosphere. The recognition of the controller is simple and straight forward.

Tapping method AFM has a relatively leisurely scan speed compared with different imaging methods. The maximum accessible scan speed is limited by the bandwidth of the *z*-axis feedback loop, which is inversely proportional to the quality (*Q*) factor of the detecting cantilever. Momentous increases in scan speed have been established with the use of active *Q* control to decrease the cantilever *Q* factor [5-7]. The piezoelectric shunt control system makes use of a self-actuated piezoelectric microcantilever, which has a sheet of piezoelectric material devoted to the cantilever beam.

A sinusoidal voltage is applied to piezoelectric actuator to oscillate the cantilever while working in tapping method. As shown in fig. 1. The probe tip is oscillated at, or close to, the cantilever's first resonance frequency while the sample is scanned beneath the cantilever, typically in a raster pattern, using a piezoelectric scanner. A 3-D image of the sample topography is generated by recording the output of the z-axis feedback controller, which maintains the cantilever oscillation amplitude at a set point value by raising or lowering the height of the sample stage. As the cantilever displacement is sinusoidal, delaying the signal by $\pi/2$ rad, with a time delay circuit, provides an estimate of the tip velocity. This is the most common implementation of active Q control in commercial AFMs.
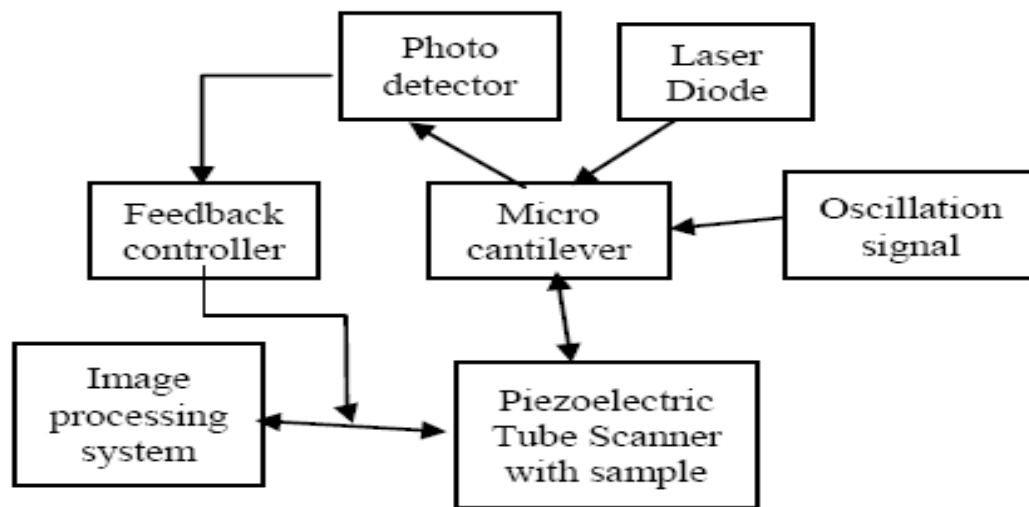
Fig: 1. tapping mode AFM

One disadvantage of using the time delay technique [8] of velocity estimation is that spill-over effects from the control action may affect higher order modes of the cantilever, leading to likely degradation of system performance. The feedback signal used for most operations of active Q control relies on the displacement signal achieved from the optical sensor [9]. The optical deflection sensing method used to calculate the cantilever tip displacement in profitable AFMs presents a major amount of noise into the deflection measurement. In addition to electronic noise, two other types of noise are familiarized by the optical sensor.

The first type of noise presented by the optical sensor is due to stray beams of light reflecting off the sample surface and back into the sensor. The second type of noise is due to light reflecting back from the cantilever and the sample into the laser source. Imaging in a liquid atmosphere is mostly difficult due to reflection and refraction of the laser beam at the interface between air and water. Other problems of optical deflection sensing method comprise the time taken to align the laser beam and the size of the sensor. The mission of aligning the laser beam must be finished every time that the cantilever is changed. This is deadly and time consuming task. The optical sensor inhabits a relatively huge amount of space. Decreasing the size of the sensor is the benefit for applications which use an array of cantilevers and to decrease the size of the AFM. The method of active piezoelectric shunt control is used modify the effective Q factor of a piezoelectric self-actuated AFM micro-cantilever, eliminates the optical sensor from the Q control feedback loop. If the cantilever displacement can be calculated with the piezoelectric transducer then it is possible to eliminate the optical sensor from the AFM altogether, overcoming the restrictions of the optical sensing method.

2.   ACTIVE PIEZOELECTRIC SHUNT CONTROL

Passive piezoelectric shunt control [10] is a general method of controlling vibration in structures such as spacecraft [11] and aircraft components [12]. A piezoelectric transducer is bonded to the surface of the structure with passive electrical impedance connected to its electrodes. The piezoelectric transducer converts the mechanical energy of the structure into electrical energy and vice versa. The dynamics of the electrical circuit have a strong effect on the mechanical dynamics of the structure. Fairbairn et al. [13] reduced the Q factor of a piezoelectrically actuated AFM micro-cantilever using passive piezoelectric shunt control.

A synthetic impedance emulating an inductance and a resistance was placed in series with the cantilever oscillation voltage source to create an LRC circuit. This LRC circuit was tuned to the mechanical resonance of the cantilever to ensure that the electrical dynamics of the circuit had maximum effect over the mechanical dynamics of the cantilever. By tuning the resistance in the circuit a reduction in the cantilever Q factor from 297.6 to 35.5 was achieved. Passive piezoelectric shunt control cannot be used in applications where an increase in the cantilever Q factor is required to increase force sensitivity and reduce tapping forces. To increase the cantilever Q factor using piezoelectric shunt control, energy must be added to the system. This requires the design of an active impedance in the piezoelectric shunt control framework.

The concept of using active piezoelectric shunt control to increase the Q factor of a cantilever has recently been demonstrated by Zhao et al. [14] Their experiments were conducted on a large cantilever (0.043 m×0.433 m) with a resonance frequency of 91.7 Hz. An inductance and a negative resistance were connected to the terminals of a piezoelectric transducer which was bonded to the cantilever surface. To test the influence of the electrical impedance on the cantilever dynamics a separate piezoelectric transducer bonded to the cantilever was used for actuation. In this work the technique of active piezoelectric shunt control is applied to a piezoelectric AFM micro-cantilever with a resonance frequency of approximately 50 kHz. The piezoelectric layer on the surface of the cantilever is used to simultaneously oscillate the cantilever and modify its dynamics in a way that enhances the Q factor.

3.   ELECTROMECHANICAL MODEL OF THE PIEZOELECTRIC SHUNT SYSTEM

A schematic of the micro-cantilever with the attached shunt circuit is shown in Fig.2. The piezoelectric shunt control system may be modeled by the block diagram of Fig. 3. In this representation the cantilever is modeled as the system G. The cantilever has two inputs: the terminal voltage v and a disturbance strain w. This disturbance strain is a result of variations in the sample topography when scanning. The cantilever's two outputs are the tip displacement d and the charge generated at its terminals q. v_s is the voltage applied to the circuit and v_z is the voltage appearing across the terminals of the shunt impedance. The initial tip displacement due to a disturbance is represented by d_w. The transfer function from w(s) to d_w(s) is

$$G_{d_w w}(s) = \frac{d_w(s)}{w(s)} = \frac{\beta_w \omega_n^2}{s^2 + \frac{\omega_n}{Q} s + \omega_n^2}$$

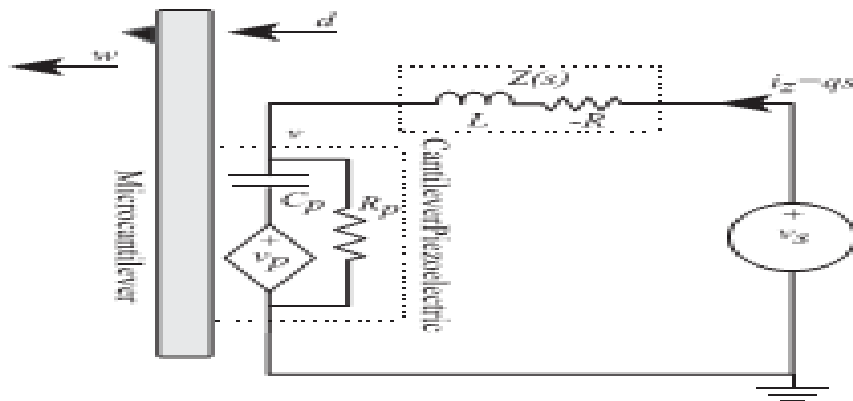Where β_w is the steady state gain of $G_{d_w w}(s)$.

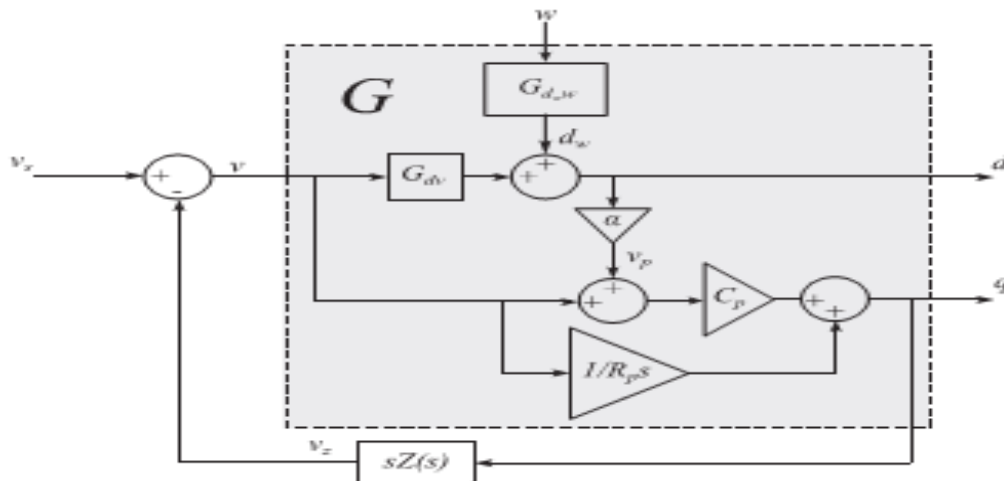**Fig: 2. Piezoelectric AFM micro-cantilever with attached shunt circuit**

Fig: 3. Block diagram of the piezoelectric shunt control system.

4.   EXPERIMENTAL RESULTS

To demonstrate the effectiveness of the active piezoelectric shunt controller, the frequency response of $H^{-1}(s)G_{dv_s}(s)$ was measured. To obtain $H{-}1(s)G_{dv_s}(s)$, H(s)was first obtained by applying a pseudorandom signal to v_s and measuring the frequency response across the terminals of the piezoelectric transducer on the cantilever. $G_{dv_s}(s)$ was then measured by applying a pseudo random signal to vs and measuring the cantilever displacement with the Polytec MSV 400. $H^{-1}(s)G_{dv_s}(s)$ was then obtained offline in MATLAB, as shown in Fig. 4. From the frequency response, a significant reduction in the cantilever Q factor can be observed.
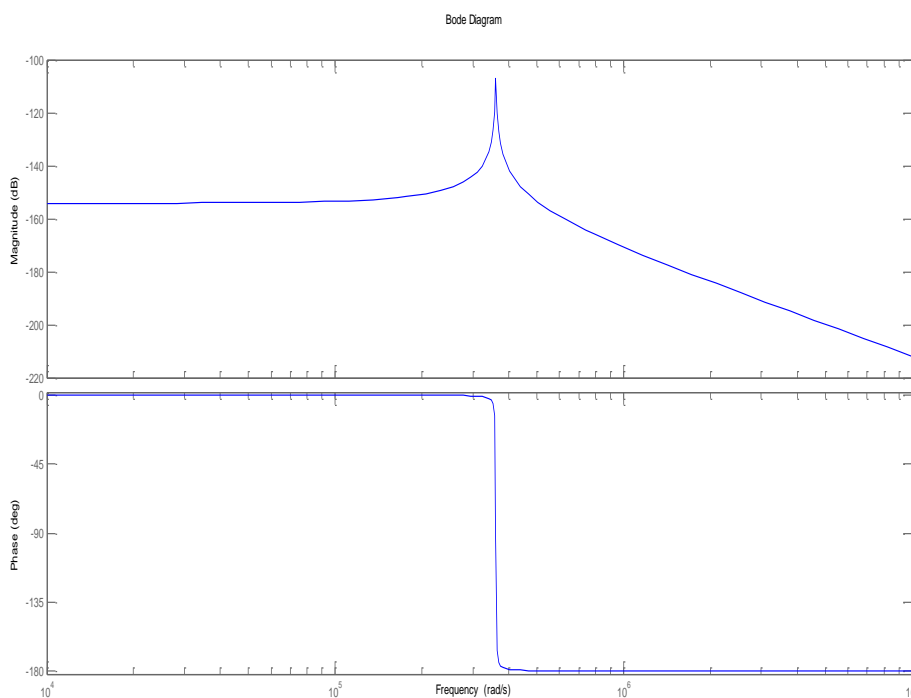

Fig: 4. Frequency response $G_{dv_s}(s)$ with the cantilever in open loop (--)

The effective cantilever Q factor may be determined from its step response. When the cantilever is approximated as a second-order system, the exponential decay rate of its step response is $\sigma = \omega_n/2Q$. ω_n is measured from the frequency response of Fig. 4 and σ is measured from the step response. The effective Q factor reduced in closed loop compared with closed loop and it can be observed.

5.   CONCLUSION

The benefits of using a low Q factor cantilever when imaging in tapping mode AFM have been highlighted in this paper. The increased force sensitivity and reduced tip-sample force as a result of decreasing the cantilever Q factor are beneficial in many imaging applications such as imaging samples with fine features, soft samples, and samples in a fluid environment. Active piezoelectric shunt control was introduced in this work as a new technique of decreasing the Q factor of a piezoelectrically actuated AFM micro-cantilever. This method of Q control has an advantage over existing Q control techniques in that it removes the optical sensor from the Q control feedback loop, reducing measurement noise in the loop. If this method of active Q control is used in conjunction with alternative methods of measuring the cantilever displacement which work by measuring the current through the piezoelectric transducer bonded to the cantilever, the optical sensor may be removed from the instrument altogether. Removing the optical sensor is not only an advantage for reducing sensor noise, it allows for a reduction in the size of the AFM which is a benefit in many applications. The compact size and low cost of the active piezoelectric shunt control instrumentation enables the active piezoelectric shunt controller to be easily integrated into existing AFMs. Piezoelectric shunt control technique is also applied to the AFM piezoelectric scanner for further reduction.

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