Mechatronic Demodulation for Dynamic Atomic Force Microscopy Measurement Modes

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***Abstract*—This paper presents the application of a mechatronic lock-in amplifier for demodulation of cantilever oscillations in dynamic Atomic Force Microscopy (AFM) measurement modes. The method is implemented using self-sensing AFM cantilevers with integrated piezoresistive deflection sensors, which are configured in AC bridge circuits for direct demodulation at the bridge circuit output. Dynamic AFM topography and phase measurements are carried out and the imaging performance is analysed. Comparison to demodulation by a conventional digital lock-in amplifier shows that the mechatronic demodulation method enables AFM imaging with significantly reduced sampling frequency without loss of imaging performance.**

***Index Terms*—Demodulation, AFM, Self-sensing cantilever, Lock-in amplifier**

I. Introduction

Dynamic Atomic Force Microscopy (AFM) imaging modes are widely used for the characterization of surfaces with sub-nanometer resolution [1]. The AFM cantilever is excited close to one of its mechanical resonance frequencies and the interaction forces with the sample lead to a modulation, i.e. a low-frequency variation of amplitude and phase shift, of the cantilever oscillation. The most commonly used dynamic AFM imaging mode is Amplitude-Modulation AFM (AM-AFM) [2], which utilizes the oscillation amplitude as control parameter to determine the surface topography. Simultaneously, the phase can be recorded providing information about local mechanical properties [3]. Similarly, the modulated cantilever oscillation is employed in a variety of functional imaging modes such as Kelvin-Probe Force Microscopy [4] and Magnetic Force Microscopy [5] to determine local electrical or magnetic surface properties. The measurement of amplitude and phase, which requires the measurement and demodulation of the cantilever oscillation, is therefore a crucial part of the control structure in dynamic AFM imaging modes.

The optical beam deflection (OBD) method [6] is widely used for measuring the cantilever deflection, as it provides low noise and wide applicability for different types of cantilevers. However, due to the finite optical beam diameter the minimum size of the used cantilevers is limited to a few micrometers. This can be a limitation for high speed imaging applications utilizing small cantilevers with high resonance frequencies. If the laser spot size is larger than the cantilever, the sensitivity of the deflection measurement is reduced and imaging artefacts due to interference of reflected laser light from the surface are more pronounced [7]. Additionally, it requires cumbersome laser guidance and alignment which typically leads to bulky and costly measurement systems. Self-sensing cantilevers with integrated piezoresistive elements can overcome these limitations [8]. They can be miniaturized for high sensitivity [9] and high frequency applications [10]. Additionally, the ability for mass production by micro fabrication enables an easy extension to cantilever arrays for parallel probing systems [11].

In addition to the detection a demodulation is required to determine amplitude and phase of the cantilever oscillation. The most widely used method is the lock-in amplifier [12], which mixes the deflection signal with a reference oscillator to enable a narrow-band measurement of amplitude and phase. For high speed imaging single-wave methods such as the peak-hold method [13] and the coherent demodulator [14] have been used enabling a fast amplitude and phase measurement at the cost of a higher susceptibility to other components of the oscillation frequency.

With typical AFM cantilever resonance frequencies of 100 kHz to several MHz, the required sampling frequencies therefore range from hundreds of kHz up to tens of MHz for high imaging bandwidth applications [15]. The development of smaller cantilever probes as well as the advent of imaging modes using higher harmonics can require sampling frequencies beyond 100 MHz [16]. Similarly, increasing the imaging bandwidth by using multi probe AFM systems can require multiple channels of simultaneous and fast demodulation with high resolution. The implementation of demodulators can therefore present a significant challenge for the development of dynamic AFM measurement modes with high imaging bandwidth.

The contribution of this paper is the implementation of dynamic AFM measurement modes with self-sensing cantilevers and a mechatronic lock-in amplifier [17], which enables a significant reduction of the sampling frequency without loss of performance. The mechatronic lock-in amplifier is integrated with a commercial AFM system and the imaging performance is compared to the results obtained using a conventional lock-in amplifier for demodulation. To demonstrate the applicability of the method for AFM imaging, topography

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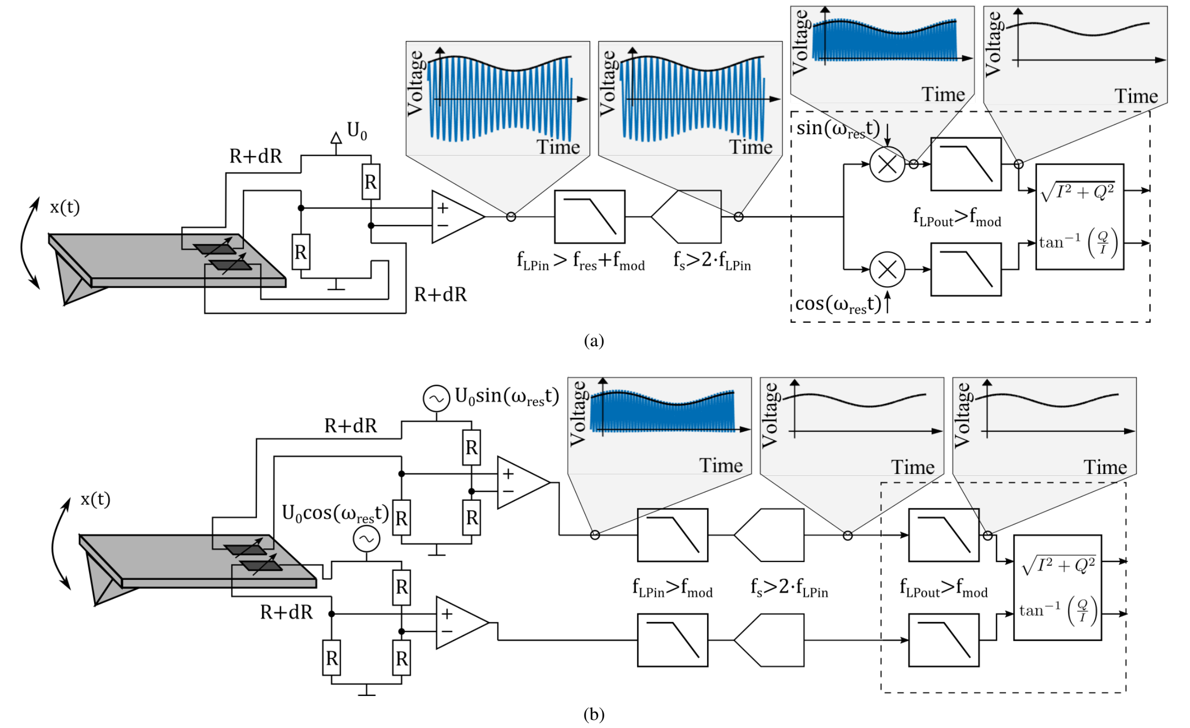

Fig. 1: Illustration of piezoresistive deflection measurement and demodulation of AFM cantilever oscillation. (a) Conventional demodulation by lock-in amplifier. (b) Mechatronic demodulation.

and phase measurements are performed using AM-AFM with simultaneous phase imaging. In Section II the demodulation of the AFM cantilever oscillation by the mechatronic lock-in amplifier is explained. The experimental setup is described in Section III. In Section IV the AFM imaging results are discussed. Section V concludes the paper.

II. Demodulation by Mechatronic Lock-in Amplifier

The mechatronic lock-in amplifer used for the measurement of amplitude and phase of the AFM cantilever oscillation in this paper is described in detail in [17], [18]. In this Section, the working principle of the method in regard to its application for AFM measurements and the differences to the conventional lock-in amplifier are discussed. The explanation is based on the assumption that the cantilever is used for a topography measurement in AM-AFM. Thus, it is assumed that the cantilever is mechanically excited, e.g. by a dither piezo, and the measured oscillation amplitude is fed back to a controller which adjusts the tip-sample distance such that the amplitude maintains constant. However, the presented method is not limited to this application, but can be used for various dynamic AFM measurement modes which use either the amplitude or the phase shift as control or measurement parameter.

Figure 1a shows detection and demodulation of the oscillation of a self-sensing AFM cantilever using a conventional lock-in amplifier. It is assumed that the cantilever oscillates at or close to its resonance frequency f_{res}. Due to interaction with the surface the oscillation is modulated. The resulting oscillation is therefore given by

$$x(t) = A(t) \cdot \sin(2\pi f_{res} t + \phi(t)) \,, \tag{1}$$

where both amplitude $A(t)$ and/or phase $\phi(t)$ of the cantilever oscillation are time dependent and vary with the modulation frequency $f_{mod} \ll f_{res}$. Piezoresistive elements at the base of the cantilever connected in a bridge circuit are used for measuring the deflection. The bridge output voltage is amplified by high bandwidth differential amplifiers. The measured deflection is sampled by an ADC with a preceding anti-aliasing low pass filter. The minimum required sampling frequency to enable a digital demodulation is given by $2 \cdot (f_{res} + f_{mod})$. The resulting digital signal is multiplied by in-phase and quadrature sinusoids. The output signals are applied to low pass filters to eliminate the resulting components at twice the cantilever resonance frequency. The crossover frequency of the output filter defines the achievable imaging bandwidth and has to be higher than the modulation frequency. The amplitude and phase of the cantilever oscillation is calculated from the filtered in-phase and quadrature components.

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Figure 1b shows the working principle of the mechatronic lock-in amplifier. The deflection measurement is implemented in two separate quarter bridge circuits which are supplied by AC voltages $U_0 \sin(\omega_{res}t)$ and $U_0 \cos(\omega_{res}t)$. The supply voltages therefore correspond to the in-phase and quadrature sinusoids which are used for the multiplication in the conventional lock-in amplifier. This leads to a direct mechatronic demodulation within the bridge circuit. The bridge output voltages therefore correspond to the in-phase and quadrature signals in the lock-in amplifier. In contrast to the conventional lock-in amplifier, the anti-aliasing filter at the ADC input can directly be used for eliminating the component at twice the cantilever resonance frequency. The minimum required ADC sampling frequency is therefore given by $2 \cdot f_{mod}$. The oscillation amplitude and phase are calculated in the same way as for the conventional lock-in amplifier.

Table I shows a comparison of the minimum required sampling frequency and other features of mechatronic demodulation to the conventional lock-in amplifier. For reference, common wide-band demodulation methods for high speed AFM imaging, which enable demodulation within a single cycle of the oscillation period, are included in the table as well. The minimum sampling frequencies for a digital implementation of the wide-band methods are based on [19]. Except for the peak-hold method, all methods enable a simultaneous amplitude and phase measurement. The minimum sampling frequency of the wide-band methods and the conventional lock-in amplifier is limited by the cantilever resonance frequency. In contrast, the minimum sampling frequency of mechatronic demodulation is limited by the modulation frequency.

The modulation frequency f_{mod} is directly related to the AFM imaging bandwidth $BW \propto f_{res}/Q$ which is proportional to the cantilever resonance frequency and the Q-factor [21]. The mechatronic lock-in amplifier therefore enables a reduction of the required sampling frequency by the Q-factor of the AFM cantilever, which has typical values of $100-1000$ for measurements in air. It therefore allows the use of slow high resolution ADCs which can be specifically optimized for high signal-to-noise ratio. A disadvantage of the method is the requirement for two independent bridge circuits leading to a reduction of the sensitivity by a factor of 2. However, this disadvantage could be alleviated by integrating 4 or 8 piezoresistive elements in two half-bridge or full-bridge circuits.

III. Experimental Setup

To verify the applicability of the mechatronic lock-in amplifier for dynamic AFM measurements, topography and phase measurements are performed by AM-AFM. For comparison, AM-AFM is implemented both with a conventional lock-in amplifier and with the mechatronic lock-in amplifier. To this end a commercial AFM system (Dimension, Bruker, Billerica, USA) is modified to enable measurements with self-sensing cantilevers. The used self-sensing AFM cantilever (PRSA-L300-F80-Si-PCB, SCLSensortech, Vienna, Austria) has two integrated piezoresistive elements at its base and a resonance frequency of 91 kHz. The cantilever and its connector are glued to a dither piezo, which itself is glued to a custom mount to the AFM scanner. The bridge circuits, the instrumentation amplifiers and the input filters shown in Figure 1 are implemented on a custom-made PCB. The PCB is described in detail in [17]. Figure 2 show a close-up of the cantilever holder and the custom-made PCB with a denotation of all its parts. Figure 3 shows an image of the experimental setup.

For the implementation of the conventional lock-in method (Figure 1a), a digital lock-in amplifier is implemented on a

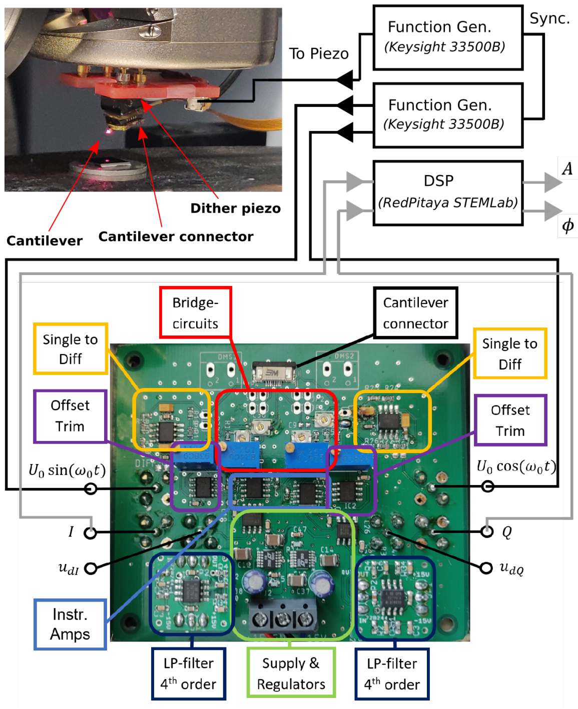

Fig. 2: Close-up of the cantilever holder, image of the custom-built PCB and block diagram of the demodulation method. The figure is adapted from [17].

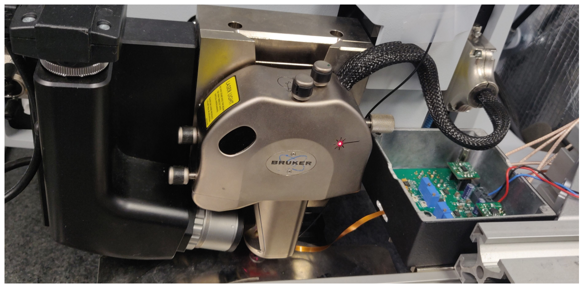

Fig. 3: Image of experimental setup.

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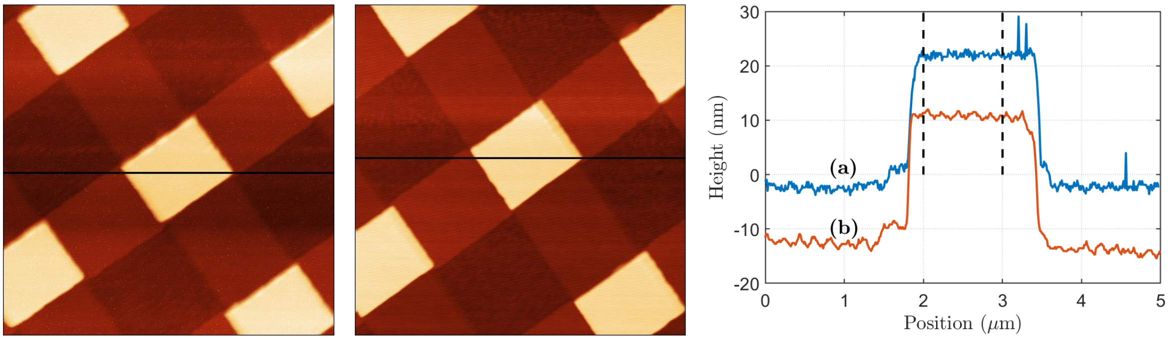
TABLE I: Qualitative comparison of mechatronic demodulation to conventional demodulation methods.

Method	Min. f_s	Type	Phase
Peak-hold [13]	$4 \cdot f_{res}$	wide-band	no
Coherent demodulation [14]	$3 \cdot f_{res}$	wide-band	yes
Lock-In amplifier [20]	$2 \cdot (f_{res} + f_{mod})$	narrow-band	yes
Mechatronic demodulation	$2 \cdot f_{mod}$	narrow-band	yes



(a) (b) (c)

Fig. 4: AM-AFM topography measurements of TGQ1 test grating. The scan size is $5 \times 5 \mu$m and the scan rate is 1 line/second. The range of the color scale is 40 nm. Measurement with self-sensing cantilevers and (a) conventional demodulation by lock-in amplifier and (b) mechatronic demodulation. (c) Cross-sections of the topography images. The curves are offset by a constant value for better visibility. The black dashed lines indicate the range used for the calculation of the standard deviation (see description in the text).

RedPitaya FPGA board with 14-Bit ADCs. The bandwidth of the input filter is set to 1 MHz and the output filter bandwidth is chosen as 10 kHz. The input filter is implemented as 4th-order analog filter integrated on the PCB. The output filters are implemented as 2nd-order digital filters on the RedPitaya FPGA board. For the implementation of the mechatronic lock-in amplifier (Figure 1b), only the output filter and the calculation of amplitude and phase from the in-phase and quadrature signals are implemented on the RedPitaya FPGA board. Both the input and the output filter bandwidth are chosen as 10 kHz. To enable a fair comparison of the imaging performance of the two methods, both digital systems are implemented on the same type of FPGA system with high speed ADCs. However, since the input filter bandwidth is chosen as 10 kHz for the mechatronic demodulation, it is clear that the method can be operated with significantly reduced sampling frequency. To enable AFM imaging the demodulated amplitude and phase are applied to the Nanoscope V controller of the AFM system via a signal access module.

IV. AFM Imaging

Figure 4 shows AM-AFM topography measurements on a test grating (TGQ1, NT-MDT, Moscow, Russia) with a structure height of 25 nm. In Figure 4a the topography measurement is performed using demodulation by a conventional lock-in amplifier. Figure 4b shows a measurement using the mechatronic lock-in amplifier. The comparison shows no significant differences of the imaging performance of the two methods.

For a further analysis, cross sections indicated by the black horizontal lines are shown in Figure 4c. The curves corresponding to the AFM images in Figure 4a and Figure 4b are labelled accordingly. Constant offsets are added to the curves for better visibility. The cross sections of both topography measurements (a) and (b) reveal small oscillations due to power line interference. The oscillations appear to be larger for the implementation with the mechatronic lock-in amplifier (b). However, the standard deviations of the topography signals between the black dashed lines in Figure 4c equal 478 pm and 474 pm for the conventional and the mechatronic lock-in amplifier, respectively. The imaging performance of the two methods is therefore almost identical. The results show that the mechatronic lock-in amplifier enables dynamic mode AFM measurements with similar imaging performance as a conventional lock-in amplifier.

The topography measurement by the conventional lock-in amplifier shows several distinct peaks which are probably due to interference of high frequency noise from adjacent noise sources in the laboratory. A possible reason why the peaks are not visible when using the mechatronic lock-in amplifier is the reduced input filter cross over frequency, which can lead to an improved noise suppression. However, the investigation

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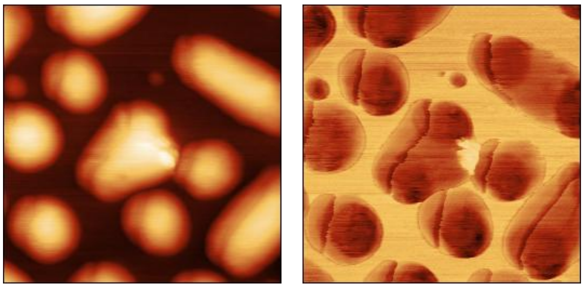

(a) (b)

Fig. 5: AM-AFM images of PS-LDPE sample using mechatronic demodulation. The scan size is $10 \times 10\mu$m and the scan rate is 0.25 lines/second. (a) Topography image (range of color scale is 200 nm). (b) Phase image (range of color scale is $6°$).

of this effect requires a more detailed noise analysis which is beyond the scope of this paper.

To verify the measurement of both oscillation amplitude and phase by the mechatronic demodulation method the phase is recorded during an AM-AFM image of a PS-LDPE sample in Figure 5. The sample consists of a combination of different polymer materials which show a distinct phase contrast due to different mechanical surface properties [22]. Figure 5a shows the topography of the sample which is measured by AM-AFM using the mechatronic lock-in amplifier in the same way as in Figure 4b. Figure 5b shows the phase image which is recorded simultaneously. The vertical lines on the phase measurements are likely artefacts due to a damaged tip, since they appear identically on all structures. However, the phase contrast of the two materials is clearly visible in the image.

In summary it has been shown that mechatronic demodulation enables a reduction of the required ADC sampling frequency in dynamic mode AFM measurements by a factor of 100 without loss of performance.

V. Conclusion

Amplitude-Modulation AFM topography imaging is implemented with a mechatronic lock-in amplifier, which enables measurement of amplitude and phase of the cantilever oscillation with significantly reduced ADC sampling frequency. AFM topography measurements using mechatronic demodulation are performed and compared to the results obtained with a conventional lock-in amplifier. The mechatronic and the conventional lock-in amplifier implementations show an almost identical imaging performance with a topography noise level of 474 pm and 478 pm, respectively. While the conventional implementation of a digital lock-in amplifier requires sufficiently high sampling frequency to capture the resonance frequency of the cantilever, the sampling frequency of the mechatronic lock-in amplifier is defined by the modulation frequency. For the cantilever resonance frequency of 91 kHz used in this work, the required ADC sampling frequency is reduced by a factor of 100 from 1 MHz to 10 kHz. It is expected that the mechatronic demodulation method can simplify the development of dynamic AFM modes, especially for applications requiring high imaging bandwidth.

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