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Control of the higher eigenmodes of a microcantilever: Applications in atomic force microscopy

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ABSTRACT

While conventional techniques in dynamic mode atomic force microscopy typically involve the excitation of the first flexural mode of a microcantilever, situations arise where the excitation of higher modes may result in image artefacts. Strong nonlinear coupling between the cantilever modes in liquid environments may result in image artefacts, limiting the accuracy of the image. Similar observations have been made in high-speed contact mode AFM. To address this issue, we propose the application of the modulated–demodulated control technique to attenuate problematic modes to eliminate the image artefacts. The modulated–demodulated control technique is a high-bandwidth technique, which is well suited to the control of next generation of high-speed cantilevers. In addition to potential improvements in image quality, a high-bandwidth controller may also find application in multifrequency AFM experiments. To demonstrate the high-bandwidth nature of the control technique, we construct an amplitude modulation AFM experiment in air utilizing low amplitude setpoints, which ensures that harmonic generation and nonlinear coupling of the modes result in image artefacts. We then utilize feedback control to highlight the improvement in image quality. Such a control technique appears extremely promising in high-speed atomic force microscopy and is likely to have direct application in AFM in liquids.

1. Introduction

The atomic force microscope [1] employs a microcantilever with an atomically sharp tip on its free end to interrogate the surface of a sample. Originally operated in contact mode, the most notable improvement offered by dynamic mode AFM techniques is the reduction of tip–sample forces, which enables noninvasive imaging of sensitive samples. Amplitude modulation AFM, also known as *tapping mode* AFM [2] when the tip makes intermittent contact with the sample, is perhaps the most widely used AFM mode; suitable for operation in air and liquid, it can accurately estimate the topography of a sample's surface.

Conventional tapping mode AFM involves the excitation of the first flexural mode of the microcantilever, disregarding the presence of higher modes. However, a complete understanding of the imaging process necessitates consideration of the multimodal nature of the microcantilever. Nonlinear coupling between cantilever modes in liquid AFM may result in image artefacts [3–5]. High-speed contact mode AFM scans may also exhibit artefacts owing to excitation of higher modes of the cantilever [6–8]. At present, very few solutions exist to address these problems. While the sensor can be calibrated to ignore contributions from higher modes [5], this approach is tedious and lacks robustness. Feedback control can be employed with much greater success.

In this contribution, we demonstrate that strong nonlinear coupling of the tip and sample, combined with the highly resonant, multimodal nature of the microcantilever, may cause image artefacts and we utilize modulated–demodulated control in their mitigation. Such a technique may be particularly relevant for high-speed AFM imaging in liquid. Modulated–demodulated control is a vibration control technique that is suitable for the control of high-frequency resonant dynamics. We have developed a high-bandwidth modulated–demodulated controller [9,10], which can be configured using low-bandwidth, reconfigurable controllers in the baseband, thus simplifying the controller implementation. In this work, the controller was designed to offer independent control of a specific mode, without affecting adjacent modes. We experimentally verified that the application of modulated–demodulated control significantly reduced image distortion.

Another potential application of modulated–demodulated control is in the emerging field of multifrequency AFM. Several multifrequency techniques have been developed, including multiharmonic imaging [11–13], bimodal excitation [13–16], band excitation, torsional harmonic AFM and nanomechanical

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holography [13]. In such applications it may be advantageous to independently control the characteristics of each mode without affecting the adjacent modes. Such multimodal Q control has already been demonstrated in AFM [17].

2. Image artefacts in AFM

2.1. Overview of image artefacts

While the atomic force microscope is capable of obtaining accurate images detailing nanometer-scaled features, image artefacts may appear as a result of component limitations.

Many commercial atomic force microscopes utilize piezoelectric tube scanners to move the sample in the x, y and z directions. However, piezoelectric ceramics are nonlinear and may suffer from thermal drift, creep and hysteresis, which produce distortions in the image [18,19]. The resonant nature of piezoelectric tube scanners and cross-coupling between the axes further limit the achievable performance. Without closed-loop control, it can be difficult to make accurate measurements [20,21]. The selection of amplitude setpoint and feedback parameters is also important in the recovery of accurate surface estimates and even experienced operators must often determine good operating conditions by trial and error.

In addition, the probe itself can cause image artefacts. Since the image is the convolution of the tip and the feature, the quality of the tip plays a significant role in the images [18]. For accurate images, the tip must remain atomically sharp and free from contamination. The angle of the microcantilever with respect to the sample may affect the shape of sharp features.

2.2. Excitation of the higher modes of a microcantilever

The excitation of higher cantilever modes is another cause of image artefacts, particularly when there is strong nonlinear coupling between the modes.

Performing AFM scans in liquid environments can often be challenging owing to the low Q factors and nonlinear effects of the liquid environment. Experiments have shown that the higher eigenmodes can be excited via tip–sample contact and modes can be nonlinearly coupled [3–5]. While the excitation of higher modes may offer more insight into properties of the sample, it is also likely that such coupling may result in image artefacts. One proposed solution to overcome this limitation is to calibrate the sensor to ignore contributions from the higher mode [5], however this solution is tedious to implement and lacks robustness.

The effect of oscillatory flexural modes in contact mode AFM has been investigated [6,7], highlighting that strong nonlinear coupling of the tip and the sample results in the excitation of higher modes, which adversely affects image quality. Furthermore, the excitation of higher modes was responsible for image distortion in high-speed contact mode scans using spiral scan patterns [8]. With high setpoint amplitudes and low tip–sample forces, tapping mode AFM is rarely affected by image artefacts resulting from the nonlinear coupling of the modes. In fact, the higher modes often contain useful information, which has resulted in the development of dynamic mode multifrequency AFM techniques [13]. However, it is possible to establish highly nonlinear operation in tapping mode AFM with low setpoints. Such an experiment was set up in order to demonstrate the role of feedback control in the mitigation of image artefacts caused by the excitation of higher modes and to highlight the high-bandwidth nature of the proposed solution. Fig. 1 illustrates artefacts in the images of an NT-MDT TGZ1 calibration grating, which are due to the excitation of the second flexural mode and its nonlinear coupling to the first mode.

3. Control of the higher modes of a microcantilever

Conditions do occur where the excitation of higher modes can have an adverse effect on the estimated surface topography. Such situations are likely to become even more prevalent in high-speed scanning. Since higher eigenmodes are typically characterized by high quality factors, one way to address the issues caused by the excitation of higher modes is to utilize Q control techniques to attenuate these modes.

Since the introduction of Q control in AFM [22], a plethora of advanced techniques have been developed, including adaptive control [23–26], full state feedback control [27], optimal stochastic control [28,29], observer based techniques [30,31], piezoelectric shunt control [32,33] and parametric resonance [34]. Many of these techniques are difficult to implement at high frequencies, which complicates the control of higher modes. Therefore, we propose the application of modulated–demodulated control to the control of higher modes of a microcantilever in AFM.

4. Modulated–demodulated control

Modulated–demodulated control is a vibration control technique, applicable to systems possessing high-frequency resonant dynamics. Modulated–demodulated control systems have found application in gyroscopy [35,36], gravity gradiometry [37–39], vibration damping in flexible structures [40], dynamic phase compensation [41] and more recently, in atomic force microscopy [9]. Advantages of the modulated–demodulated control technique include the significant reduction of the bandwidth requirements of

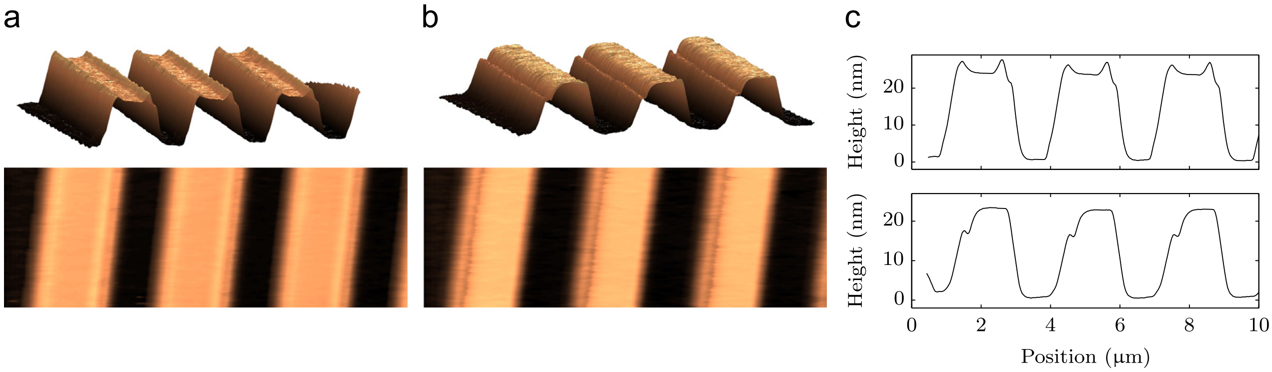

Fig. 1. AFM images of an NT-MDT TGZ1 calibration grating with high feedback gain (a) and low feedback gain (b) highlighting artefacts caused by the nonlinear coupling of the first and second flexural modes and the profile cross-sections (c). The amplitude setpoint is 25%.