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Nonlinear detection of ultrasonic vibration of AFM cantilevers in and out of contact with the sample

M T Cuberes[1,2], **G A D Briggs**[1] **and O Kolosov**[1,3]

[1] Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK
[2] Department of Applied Mechanics and Project Engineering, University of Castilla-La Mancha, Plaza Manuel de Meca 1, 13400 Almadén, Spain

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Abstract

Ultrasonic vibration can be nonlinearly detected by means of an atomic force microscopy cantilever when the tip is in contact with a sample surface owing to the so-called (sample-induced) ultrasonic force. The procedure has been developed as a novel technique, ultrasonic force microscopy (UFM), that provides information about the nanoscale elastic and adhesive properties of surfaces. Here, we compare differences in the UFM signal when ultrasound is excited from the back of the sample (sample UFM) and from the cantilever base (waveguide UFM). UFM relies on the nonlinear ultrasound-induced cantilever displacement (due to the aforementioned ultrasonic force), and does not monitor the linear high-frequency vibration of the cantilever. In this paper, we discuss the influence of a linear high-frequency cantilever response in the UFM measurements and provide experimental evidence of the feasibility of nonlinearly detecting the free ultrasonic cantilever vibration when the tip is out of contact with the sample surface using the typical laser-beam deflection method for monitoring cantilever displacements.

1. Introduction

The study of a cantilever response to ultrasonic excitation is currently attracting increasing interest [1–10]. A whole range of novel atomic force microscopy (AFM) based methods using high-frequency vibration have been proposed for the characterization of sample material properties [1–9]. In addition, some reports have already demonstrated that operation of the cantilever using higher flexural modes provides an enhanced sensitivity to force gradients in non-contact AFM [10, 11].

The usual procedure for monitoring cantilever vibration consists of tracking its response in amplitude and phase by means of a lock-in amplifier or its equivalent, using as a reference the input excitation signal. In contrast to this ‘linear’ detection mode [5, 12], when the tip is in contact with a sample surface, it is also possible to detect ‘nonlinearly’ the presence of ultrasound [1,3] owing to the so-called [3] sample-induced ultrasonic force (stemming from the nonlinearity of the tip–sample interaction). A physical mechanism that explains the activation of an ‘ultrasonic force’ when the AFM cantilever-tip is in contact with a sample surface, and the tip–sample distance is modulated at ultrasonic frequencies, is schematically illustrated in figures 1(*a*) and (*b*), and was proposed as the principle of ultrasonic force microscopy (UFM) [3, 4]. In the presence of vertical ultrasonic vibration, the tip–sample distance is varied at ultrasonic frequencies between minimum and maximum values, which depend upon the amplitude of ultrasound excitation and the initial set-point force. If the amplitude of ultrasound is small, the tip–sample distance sweeps a linear part of the force curve. The net average force that acts upon the cantilever during an ultrasonic time period will in this case be the initial set-point force. However, if the amplitude of ultrasound is increased, and the tip–sample distance is swept over the nonlinear part of the force curve, the average force now includes an additional force. Experimentally, in the presence of ultrasound of sufficient amplitude, the cantilever experiences an additional displacement (UFM signal), attributed to its response to this additional force (the ‘*ultrasonic*’ force). To date, the capabilities of UFM for mapping of mechanical

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[3] Present address: Symyx Technologies, 3100 Central Expressway, Santa Clara, CA 95051, USA.

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