Digital image processing for measuring 2D vibration amplitudes with subpixel resolution: application to the quartz tuning fork

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Abstract— **We present digital image processing techniques for measuring the vibration amplitude of a 32 kHz quartz tuning fork in the fundamental flexural mode, torsional mode and first harmonic flexural mode. The objective is to estimate the ultimate resolution of shear force scanning probe microscopy in which such a tuning fork is used for vibrating a tip over the surface being analyzed: we observe vibration amplitudes of around 350 nm/V for the fundamental flexural mode and 75 nm/V for the first flexural overtone. These values provide a fundamental limitation – beyond the probe tip size – of the spatial resolution of shear force scanning probe microscopes.**

I. INTRODUCTION

Many scanning probe microscopy techniques use the same probe with nanometric dimensions to both monitor a physical quantities (tunnelling current in Scanning Electron Microscopy, electrochemical potential in Kelvin Probe Microscopy, electrochemical current in Scanning ElectroChemical Microscopy ...) and the probe-sample distance. Such measurement techniques are suitable for homogeneous substrates on which the physical quantity is assumed to be constant, but leads to ambiguous measurements when the physical quantity changes with distance (for example in case of an evanescent field) and with probe position (heterogeneous sample). Shear force microscopy provides one possible solution of independent probe-surface distance control by vibrating the probe over the sample: the probe-sample distance is measured through the probe damping, without affecting the physical quantity measurement. This technique is widely used in Scanning Near field Optical Microscopy (SNOM [1]) in which a constant probe-sample distance is a fundamental requirement for an accurate measurement of the evanescent optical field generated close to the surface.

The drawback of vibrating the probe over the surface is that the spatial resolution is no longer solely related to the probe end-diameter but also to the vibration amplitude. The larger the amplitude the greater the interaction distance and hence the better the probe-sample distance signal. Gluing the probe to a quartz crystal tuning fork has been a well known technique since it provides a reproducible means for monitoring the tip-sample interaction through the piezoelectric response of the tuning fork [2].

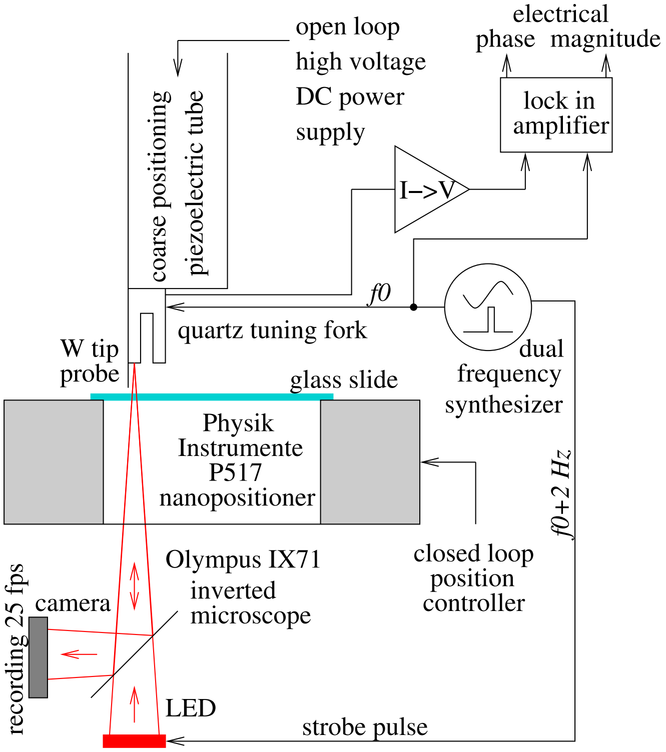

Fig. 1. General experimental setup based on a lab-made shear force scanning probe microscope mounted on an inverted optical microscope: the tungsten tip probe is attached to one prong of a quartz tuning fork fixed to a coarse positioning open-loop piezoelectric actuator. The sample is a thin glass slide attached to a closed-loop nanopositioner attached above the lens of the optical microscope. In the current setup, the camera output of the microscope is connected to a CCD sensor for recording at 25 fps the image of a grid patterned at the end of each prong of the tuning fork. The illumination is provided by a strobed LED injected through a semi-transparent plate so that the light beams follow the red lines in the figure.

We here use the tuning fork both for the excitation step (application of an AC voltage) and the detection (measurement of the current flowing through the tuning fork associated to the vibration amplitude and phase) [3]. Monitoring either phase or amplitude of the tuning fork provides an accurate measurement of the probe-sample distance. We here aim at characterizing the vibration amplitude of the tip interacting with the surface in such a setup. Furthermore, we have developed a technique able to monitor the 2D – in plane – vibration amplitude and characterize long term drift of the sample position with respect to the probe with nanometer resolution (Fig. 1).

II. EXPERIMENTAL METHODS

We use a stroboscopic video acquisition technique [4]–[6] for recording the image of a grid patterned at the end of the tuning fork as a function of time. The strobed illumination signal is generated at an offset frequency of 2 Hz with respect to the tuning fork excitation voltage. A Fourier transform based image processing technique [6] has been developed for identifying the 2D translation and in-plane rotation of the tuning fork prong with respect to the camera. Since the camera is fixed with respect to the sample, we hence monitor the tuning fork prong position with respect to the sample. We then assume this measurement to be representative of the tip-sample interaction since the tip is assumed to be rigidly glued to the tuning fork prong.

Although the technique requires the patterning of the tuning fork, this limitation is usually reduced by including the Focused Ion Beam (FIB) writing step in the MEMS fabrication flow chart. As opposed to other interferometric displacement measurement methods [7] which only provide out-of-plane one dimensional displacement information, here a simple video recording provides 2D and in plane torsional informations.

III. RESULTS

We have monitored the torsional mode which was expected to provide the largest 2D interaction path of the probe with the sample per period ; the first flexural overtone, and the commonly used fundamental flexural mode [6]. We have observed that both unloaded prongs (no probe tip glued to one of the prong) vibrate with the same amplitude which displays a response as a function of frequency following the classical electrical response of a high-quality factor resonator (Figs. 2 and 3). The mechanical quality factor is observed to be around 3600 and 1000 for the fundamental and overtone flexural modes respectively, consistent with electrical admittance measurements.

Our objective during this study was to identify the vibration amplitude of the tuning fork and assess the validity of extending free space vibration amplitude measurements on unloaded prongs to tip loaded prongs interacting with a sample surface. Fig. 4 displays the vibration amplitude extracted from videos during three tip approach phases. These are preliminary calibration curves we perform each time we install a new tuning fork: the probe is brought in contact with the surface and retracted multiple times in order to measure the signal (current magnitude and phase) as a function of probe-sample distance. This figure (top) clearly displays the time intervals when the tip is far from sample (large amplitude in the beginning, end and two intermediate retracted positions) and when in contact with the sample (3 approach curves). Furthermore, this curve clearly demonstrated a drift of the probe position which we attribute to a stabilization of the coarse piezoelectric actuator to which the tuning fork is attached. The drift is observed for the first 3000 frames or, at 25 frames/second, for the first two minutes: we wait for about 15 minutes after the tip is brought in contact with the surface before starting a sample scan. This result is consistent with our drift observation of the tip-sample feedback during scans when insufficient settling time was given to the coarse piezoelectric actuator.

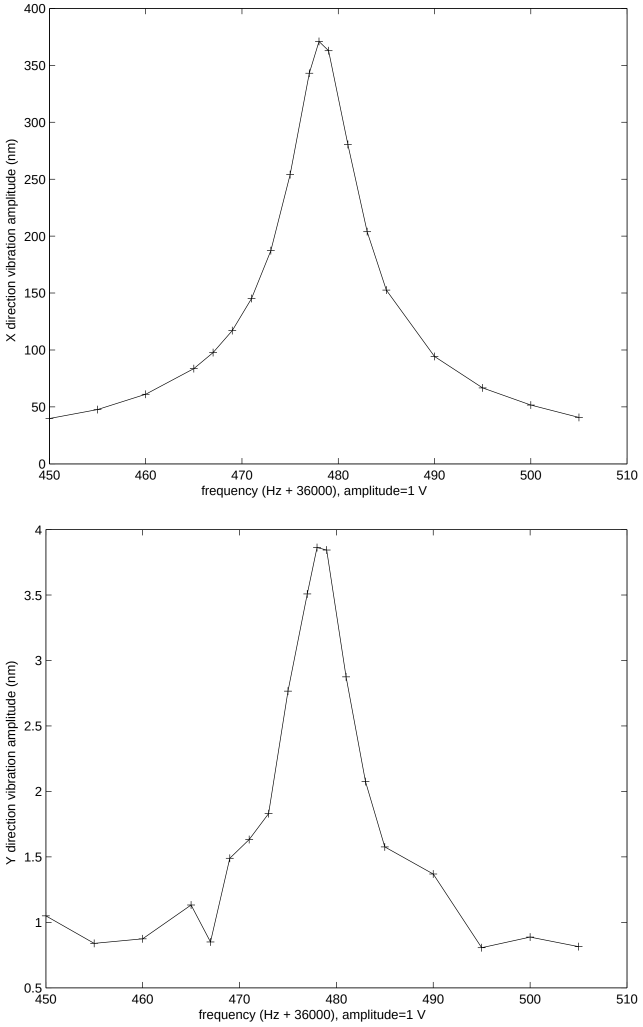

Fig. 2. Displacement measurement of a bare tuning fork prong (no tip loading) as a function of frequency around resonance. The maximum vibration amplitude is found at the maximum current magnitude while the vibration amplitude at minimum phase (36488 Hz) around one quarter of the maximum vibration amplitude. The high resonance frequency of this tuning fork is due to the polishing of the prongs, performed for allowing a clean surface for FIB patterning of the periodic pattern. The voltage applied to the tuning fork for generating the vibration is 1 V amplitude.

We have observed that a bare tuning fork (without probe glued to one of the prongs) behaves symmetrically with no significant difference in the vibration amplitude of one of the prongs. We have observed that the vibration amplitude of the prong loaded with a tungsten tip is 10% less than the unloaded

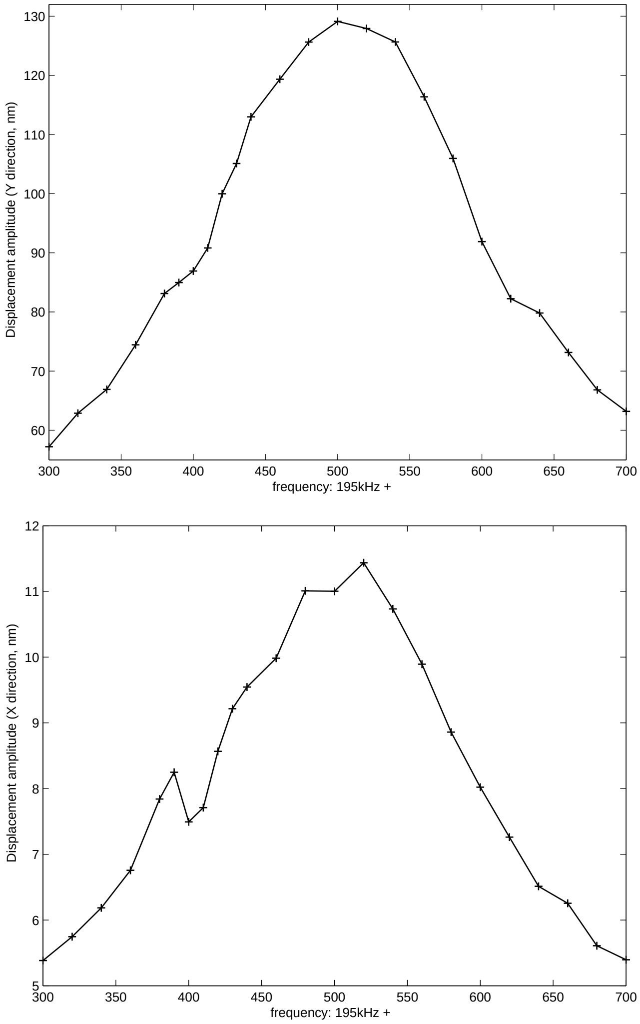

Fig. 3. Vibration amplitude as a function of frequency for the flexural mode overtone around 195 kHz.

prong: hence, observing the unloaded prong is a good indicator of the vibration amplitude of the tip, possibly easier to access in most scanning probe microscopy setups than the loaded prong.

We have furthermore observed the vibration amplitude of the prong during the scans of two lines along a periodic structure array etched on glass (Fig. 5). We have simultaneously recorded the electrical phase on which the feedback for keeping the tip-sample distance constant was applied, as well as the sample altitude as provided by the close loop control of the positioner. We observe on this figure that:

- multiple tip crashes occurred during which the vibration amplitude of the prong to which the probe is attached was strongly reduced, simultaneously with the phase being brought close to a 0 value (bold arrows between the top and middle graphs).
- our feedback on the phase signal is too slow since the observed phase (error signal) is mostly observed outside of the acceptable setpoint phase range (the red line on the middle graph is the setpoint phase value and the dashed green lines are the acceptable phase ranges in which no feedback is applied)
- the periodic topography of the sample is still accurately observed on the bottom graph of Fig. 6, even though multiple occurrences of poor feedback occurred (thin arrows between the bottom and middle graphs of Fig. 5).

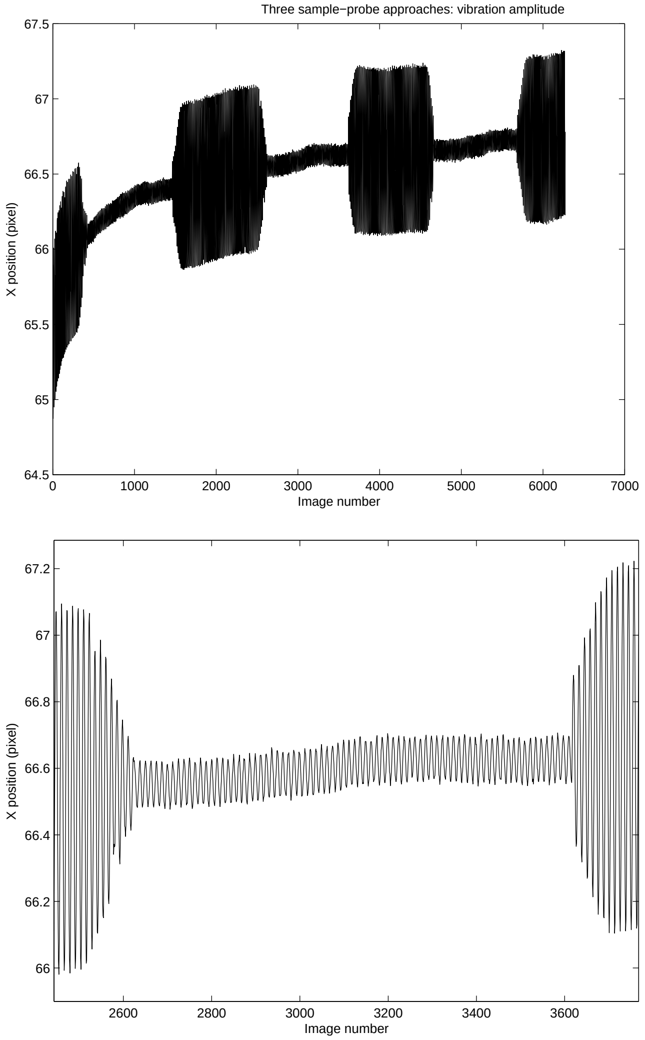

Fig. 4. Displacement measurement during force-distance curves right after switching on the coarse piezoelectric actuator to which the tuning fork is attached. The drift of the coarse piezoelectric positioner, cause of image distortion during scans, is visible on the top figure, indicating that a settling time of 5 to 15 minutes is to be observed after coarse tip approach to the surface if this drift is to be avoided. Bottom: zoom on a tip-sample contact and retraction during a force-distance curve. The continuous vibration amplitude decrease and increase as the tip gets in contact and retracts respectively from the sample is visible.

We have observed that a bare tuning fork (without probe glued to one of the Since we usually work at 50 mV excitations voltage as a compromise between good signal to noise ratio and minimum vibration amplitude, we can expect a best spatial resolution in the vibration direction of the tuning fork of about

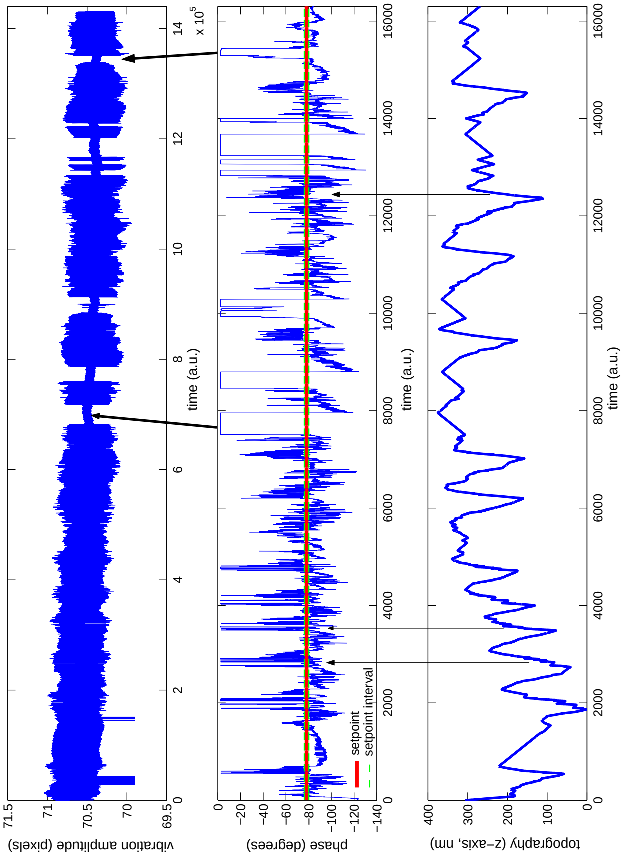

Fig. 5. Recorded tuning force phase and vibration amplitude during a scan of the probe over a periodic pattern etched in glass. The tip crash on the surface is easily observed as a phase close to 0 synchronous with a minimum vibration amplitude. Such a recording provides an educated estimate of the spatial resolution than can be reached using shear force microscopy during imaging. The bottom curve is the evolution of the tip-sample distance as the tip searches the surface until the phase setpoint is reached: the phase curve is hence mostly out of the setpoint range, while the recorded topography points recorded when the phase condition is met is presented in Fig. 6.

15 nm since we observed a linear relationship between excitation voltage amplitude and mechanical vibration amplitude. Such a resolution should allow for example the detection of a single virus (50 nm diameter) on a cell membrane.

IV. CONCLUSION

Our initial objective of assessing the vibration amplitude of a quartz crystal tuning fork in order to estimate the spatial resolution of a shear force microscope was achieved using digital image processing technique. We have shown high signal to noise ratio 2D vibration amplitude measurement for various vibration modes of the tuning fork. The experimental setup is hardly invasive since it only requires imaging the end of one of

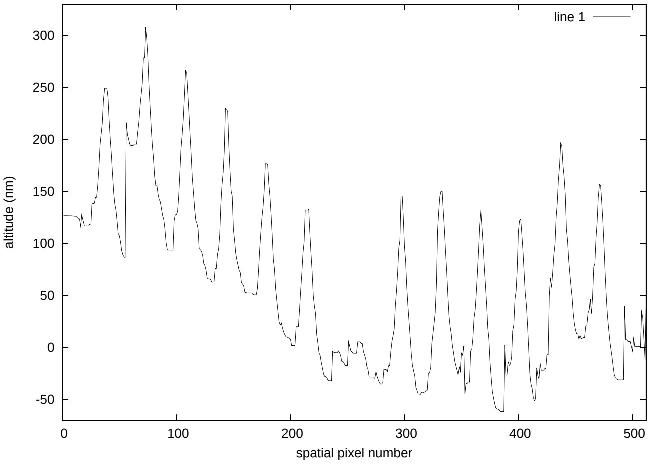

Fig. 6. Two lines of a 256 pixel topography on an glass slide etched with a periodic pattern: this scan is the result of the feedback presented in Fig. 5.

the prongs of the tuning fork, as can be easily done with any inverted microscope. The technique can be generalized to any MEMS as long as a periodic pattern is visible on the surface to be characterized. In our case this pattern was etched using a FIB after polishing the ends of the prongs.

We have experimentally observed the 2D, in plane parallel to the sample, vibration amplitude of the prong of a tuning fork used as probe in a scanning probe microscope setup. We have measured the vibration amplitude of the fundamental and overtone flexural modes and obtained a linear relationship between excitation voltage and mechanical amplitude of respectively 330 nm/V and 75 nm/V. We have observed that an interaction between the tip and the sample strongly reduces this vibration amplitude – by up to 90% depending on tip condition. We have observed reproducible vibration amplitude attenuation upon tip-sample interaction during tip-sample approach curves. We assess that the tip vibration spatial limitation of the scan is around 15 nm in our experimental condition of a 50 nm driving voltage.

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