In-plane displacement measurement with sub-pixel resolution: Application to vibration characterization of a shear-force scanning probe

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ABSTRACT

This paper reports on a sub-pixel resolution vision approach for the characterization of in-plane rigid-body vibration. It is based on digital processing of stroboscopic images of the moving part. The method involves a sample preparation step, in order to pattern a periodic microstructure on the vibrating device, for instance by focused ion beam milling. An image processing has then been developed to perform the optimum reconstruction of this a priori known object feature. In-plane displacement and rotation are deduced simultaneously with a high resolution (better than 0.01 pixel and 0.0005 rad. respectively). The measurement principle combines phase measurements - that provide the high resolution - with correlation - that unwraps the phase with the proper phase constants. The vibration modes of a tuning fork were fully characterized for the demonstration of the method capabilities. Then the tuning fork was loaded with a tungsten wire sharpened in a sub-micrometer tip for use in shear-force microscopy. The vibrations of the scanning probe were also characterized furnishing representative data on its actual vibration amplitude. The technique could however be applied to many kinds of micro-devices, for instance comb driven electrostatic actuators. For applications allowing the sample preparation, the proposed methodology is more convenient than common interference methods or image processing techniques for the characterization of the vibration modes, even for amplitudes in the nanometer range.

Keywords: in-plane vibration, sub-pixel measurement, stroboscopic imaging, position measurement, rotation measurement, tuning fork, shear force probe

1. INTRODUCTION

The question of position, displacement and vibration measurement has been a subject of interest for decades as it is a key-problem in numerous research and industrial applications. Lots of methods have been developed that are dedicated to different ranges of applications and based on different physical phenomena.[1–16] The work reported in the proceeding is concerned with the use of a low cost vision system as a tool for in-plane vibrations. A stroboscopic illumination allows a frequency shift of the inspected vibration toward the bandwidth of a standard CCD camera. The vibrating object of interest is patterned with a two-dimensional periodic grid of dots over a limited window. This a priori knowledge of these object features and the periodicity of the chosen pattern allow high-accurate phase measurements based on spectral filtering in the fourier domain. Both position and in-plane orientation of the inspected surface are reconstructed independently. Resolutions achieved by the demonstration arrangement are in the range of a few 10^{-3} pixel for the position and 0.0005 rad for the orientation. The application to in-plane vibration analysis is based on the derivation of the measured position during time. To make the motion compatible with the frame rate of a standard CCD camera, a stroboscopic illumination was chosen. The latter is driven with a 2Hz frequency shift with respect to the vibrating object excitation in order to put artificially the motion of interest on a 2Hz frequency carrier. In this paper, we first

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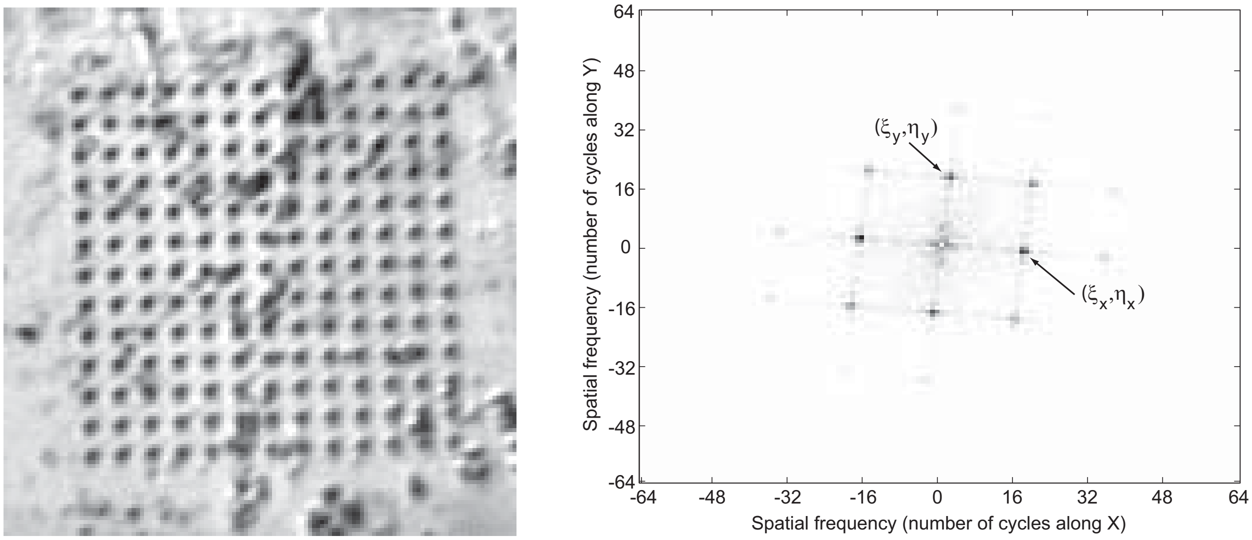

Figure 1. Left: Recorded image of the dot pattern milled by focused ion beam on the end face of the tuning-fork prong. The image is 128 × 128 pixels with a 20× magnification objective: observed area: $50 \times 50 \mu m^2$. Right: Fourier spectrum of the dot pattern image. The spatial frequencies marked by an arrow are filtered for the reconstruction of two complementary one-dimensional patterns by inverse Fourier transform.

describe the image processing developed in the determination of position and orientation in a single image of the patterned surface. A two-step procedure is involved. A fine position determination is based on the spatial phase associated with the spectral frequencies of the spatial carrier periodicity. This phase determination is subject to 2π phase ambiguities corresponding to an entire number of dot pattern periods. The latter are removed by the second step of the procedure that involves image correlation. The complete description of the method ha been reported elsewhere.[17] It has been inspired by various work published previously.[19–21]

In this work, the method was applied to the end face of a tuning fork. The latter is widely used as both a resonant device and near-field probe holder in scanning probe microscopies. The determination of the vibration amplitude is important in the description of the probe-surface near-field interaction.[18] The method proposed here is not able to detect the actual motion of the tip end but only the motion of the end face of the prong supporting the tip. Since the tip length is very short and that spurious tip resonances are easily avoided, the vibration amplitude of the prong constitutes a reliable witness of the probe damping due to tip-surface interaction. Experimental results of the characterization of the tip-loaded tuning fork vibration are presented in section 3 while effects of shear-force interactions will be presented completely at the conference presentation.

2. METHOD DESCRIPTION AND TYPICAL RESULTS

Figure 1 (left) presents the end face of one prong of a tuning fork. The visible portion of the prong was patterned by focused ion beam milling to obtain the two-dimensional set of dots. The dot period is of $3\mu m$ and furnish a size reference for further position and displacement calibration. After Fourier transform, the spatial frequencies of the regular set of dots appear clearly in the spectrum as represented in the right part of figure 1. The two perpendicular directions of the dot pattern are processed sequentially and independently. For this purpose, the spectrum is filtered in order to keep a single lobe of the spectrum as indicated by the arrows. After inverse Fourier transform, we obtain an image of complex data corresponding to a one-dimensional pattern of lines. The real part of the latter is represented in figure 2 (left). This fringe-like image is associated to a wrapped phase image that is represented in figure 2 (right). This phase map is representative for the accurate position of the one-dimensional lines versus the pixel frame of the CCD camera. The phase map is unwrap in the central part in order to avoid distorsions due to side discontinuities and we obtain the unwrapped phase map of figure 3 (left). The same processing is applied to the second spectral lobe of the Fourier spectrum (as indicated by an arrow in

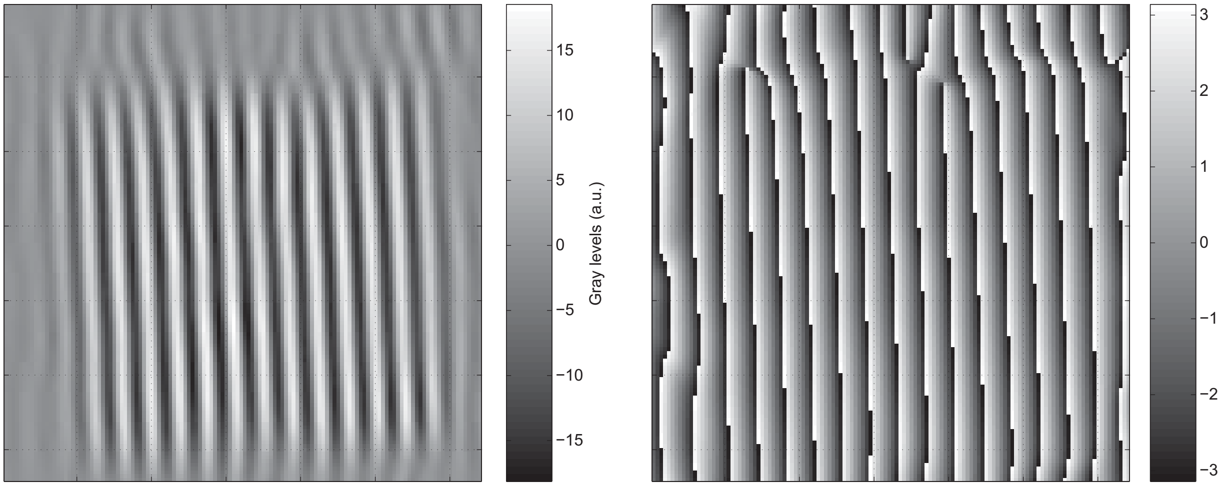

Figure 2. Left: One dimensional pattern given by the real part of the inverse Fourier transform of the spectrum of Fig.1 after filtering of the term (ξ_x, η_x). Right: Wrapped phase given by the argument of the inverse Fourier transform.

figure 1) and results in similar data in the perpendicular direction. These phase maps are fully representative of the fine positioning of the lines versus the pixel frame but it is subject to an uncertainty of $2k\pi$ since the order of the reconstructed lines has not been identified. however, the in-plane orientation and line period can be deduced directly from these data since they are not concerned with $2k\pi$ uncertainties. For the removal of these uncertainties, we process by image correlation instead of localizing the border of the line set by image treatment that is much more sensitive to image noise. From the knowledge of the dot period and orientation, we synthesize a digital image that corresponds exactly to the dot pattern feature. By correlating this expected feature with the actually recorded image, we obtain a correlation image as represented in figure 3 (right). This correlation figure presents a periodic structure because of the dot pattern periodicity. It presents also an absolute maximum that corresponds to the best matching between the synthetic digital image and the recorded one. This maximum allows a coarse determination of the dot pattern center. The latter is combined with the fine position determination provided by the unwrapped phase map and finally, the unambiguous and high-accurate position of the dot pattern center is obtained.

Typical experimental results are presented in figure 4. In the upper part, the tuning fork is excited at resonance frequency $(36478Hz)$ with a $100mV$ voltage. The LED based stroboscope illumination was driven at a frequency of $(36480Hz)$, leading to an apparent vibration frequency of 2Hz that can be resolved by a standard CCD camera. The plotted curve describes the measured dot pattern position versus time and the prong displacement during vibration can be accurately measured. The remaining mechanical instability that are responsible for drifts of the mean position can removed from the measurement by Fourier filtering centered at the 2Hz carrier frequency. For the recording of the lower part of the figure, the excitation was turned off and the resulting data are representative for the noise level of the experiment. The standard deviation observed in the position is of 5.8×10^{-3} pixel and corresponds to an actual displacement of 2.3nm. Those results were obtained with a $20\times$ magnification objective on an Olympus IX71 inverted microscope.

An interesting feature of this method is to perform also an accurate determination of the in-plane orientation of the object. Figure 5 presents the measured in-plane angle as a naked tuning fork that was excited on a torsion mode at a frequency of $181552Hz$. The measured angle resolution is about 0.0005 radian. Large angle deviations can be measured as well and the resolution was found to be quiet independent on the mean angle of the dot pattern. This angular measurement capability is a significant property of this method; that requires a sample preparation; compared with most of methods based on the analysis of the natural features of the inspected objects.

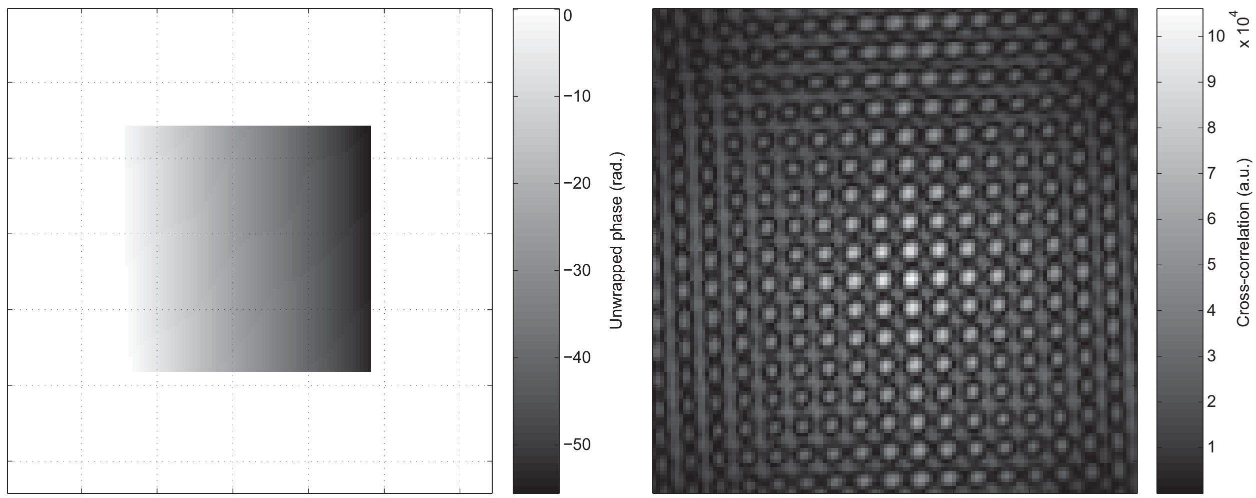

Figure 3. Left: Unwrapped phase with $2k\pi$ ambiguities. The central part is only considered for avoiding distortions due to eventual side effects. Right: Result of the cross-correlation used for the removal of $2k\pi$ ambiguities and unambiguous dot pattern centre identification.

3. APPLICATION TO THE ANALYSIS OF SHEAR-FORCE INTERACTIONS CONTROLLED BY THE TUNING-FORK VIBRATION PARAMETERS

This method for in-plane vibration measurement was applied to a tip-loaded tuning fork as used in scanning probe microscopy. In the shear force mode, the damping of the tuning fork vibration is used as an indicator of close vicinity between the near-field probe and the surface. Different servo-control methods were reported for tip-surface distance monitoring and most of them are based on lock-in detection. Several methods for tip vibration characterization were published[18, 22–24] and our method corresponds to a different approach.

The tuning fork behavior was characterized without near field probe. In this case, the two prongs are identical and they are expected to present the same vibration amplitude. This was confirmed by experiments as can be seen in figure 6 that represents the resonance curve of the tuning fork. The two prong curves superimposed perfectly and cannot be distinguished. The Q factor is about 3000. Then a tungsten near field probe was stuck on one prong side. This metal tip was obtained by tapering electrochemically a short part of tungsten wire. Figure 7 presents a view of the tip-loaded tuning fork as observed by scanning electronic microscopy.

The tip-loaded tuning fork is no more symmetrical and the prongs are subject to different vibration amplitudes. This phenomenon was observed effectively as reported in figure 8 that presents the resonance curves as measured successively on the two prongs. We observe that the tip-loaded prong has an amplitude of about 80% of the free prong one. This figure presents also the magnitude of the lock-in signal as well as the phase mismatch between the excitation signal and the current due to direct piezoelectric effect in the tuning fork. The latter signal is of practical interest since it presents an extremum that can be convenient for the servo-control of the tip position.

The vibration amplitude of the tip-loaded tuning fork was also characterized versus the excitation voltage. Experimental results are presented in figure 9 for both prongs and for two excitation frequencies; i.e. the resonant frequency and the frequency leading to the extremum of the lock-in phase mismatch. The excitation voltage dependence is linear in all cases and provides calibration data for the tuning fork vibration amplitude.

This device was inserted in a shear-force microscope and a transparent cover slip was chosen as inspected object. In this way, the end face of the prong can be imaged during shear force interaction and consecutive effects on the tuning fork vibration amplitude can be detected by the proposed method. First results demonstrate vibration attenuations due to tip sample interactions during both tip approach and object scanning. The latter were successfully quantified. however experiments are still going on for ensuring the measurement reproducibility and they will be presented during the conference presentation.

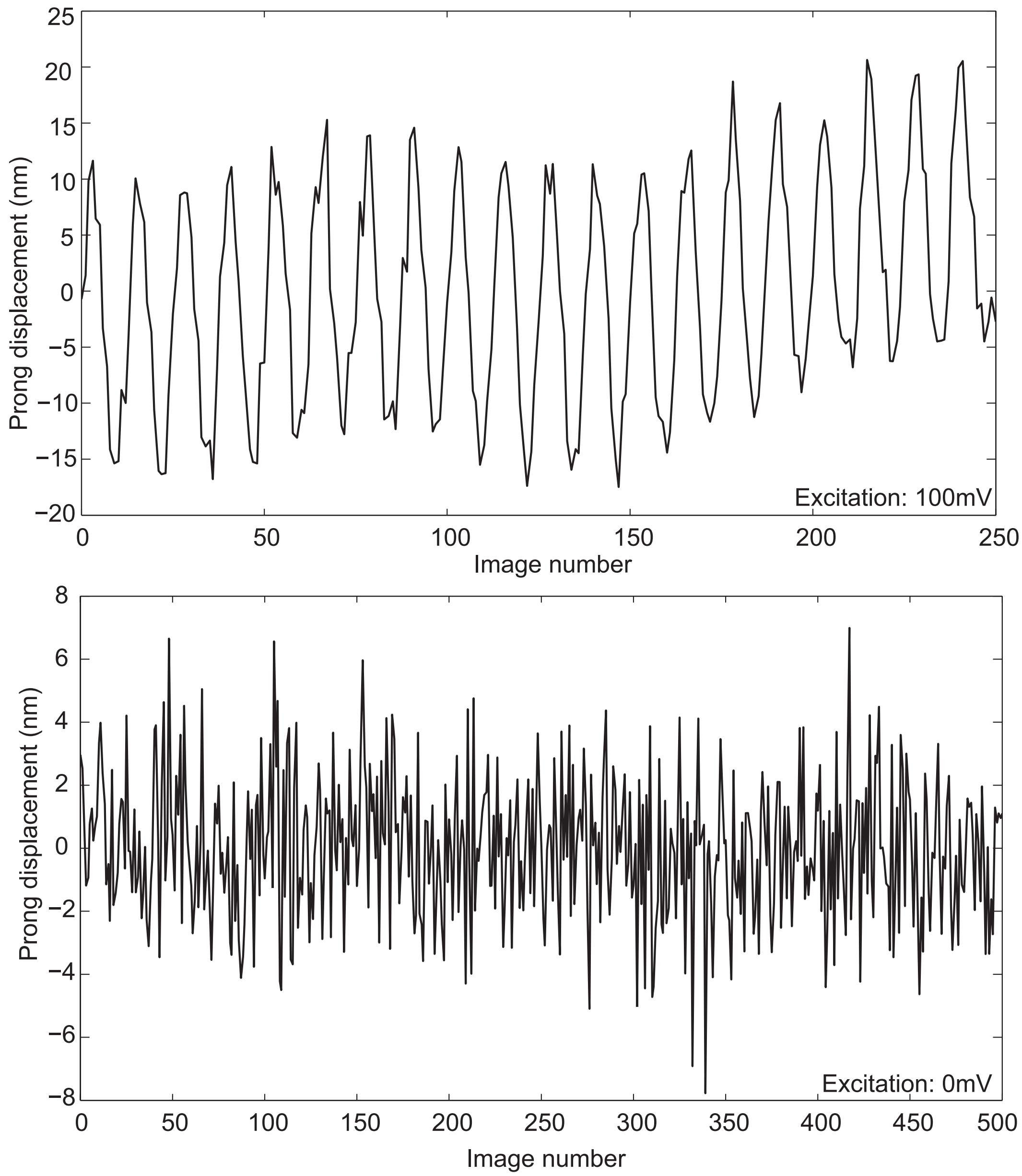

Figure 4. Measured prong position with the stroboscopic illumination. Up: tuning-fork excitation voltage of 100mV; Down: noise level without tuning-fork excitation (rms.: 2.3nm).

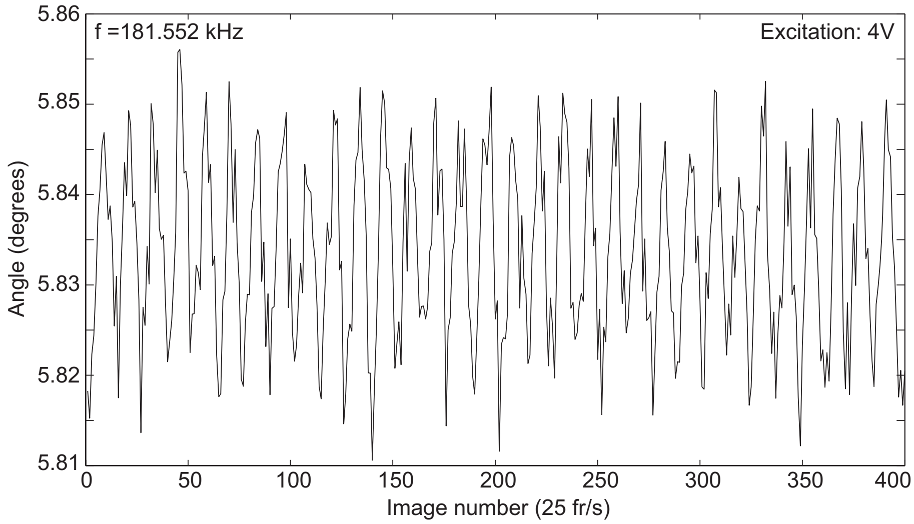

Figure 5. Angular orientation of the prong end as measured experimentally with a stroboscopic illumination.

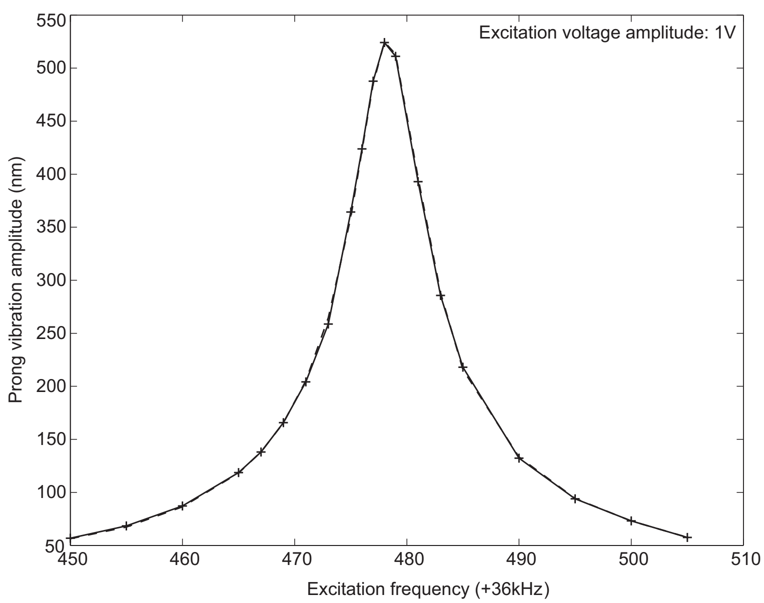

Figure 6. Prong vibration amplitude around resonance. The two prongs vibrate with the same amplitude and their curves can not be distinguished.

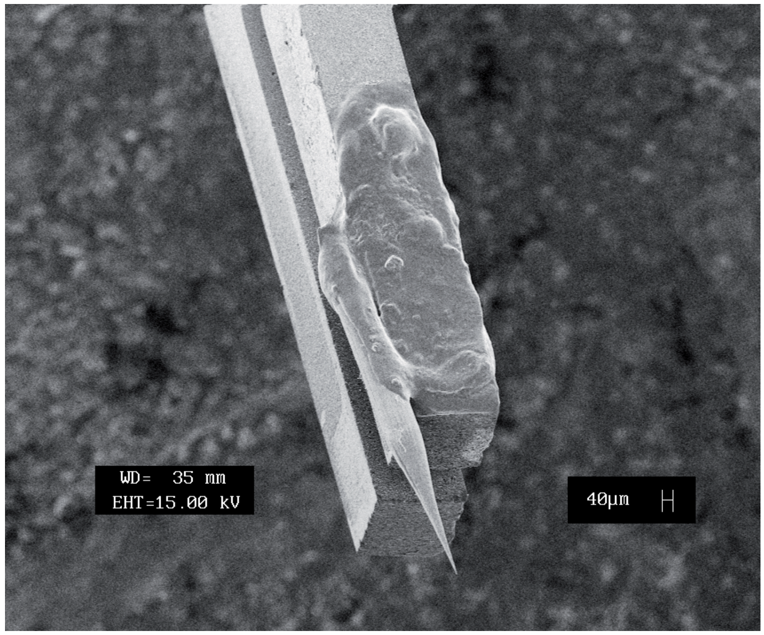

Figure 7. SEM image of the tip-loaded tuning-fork used as shear force probe.

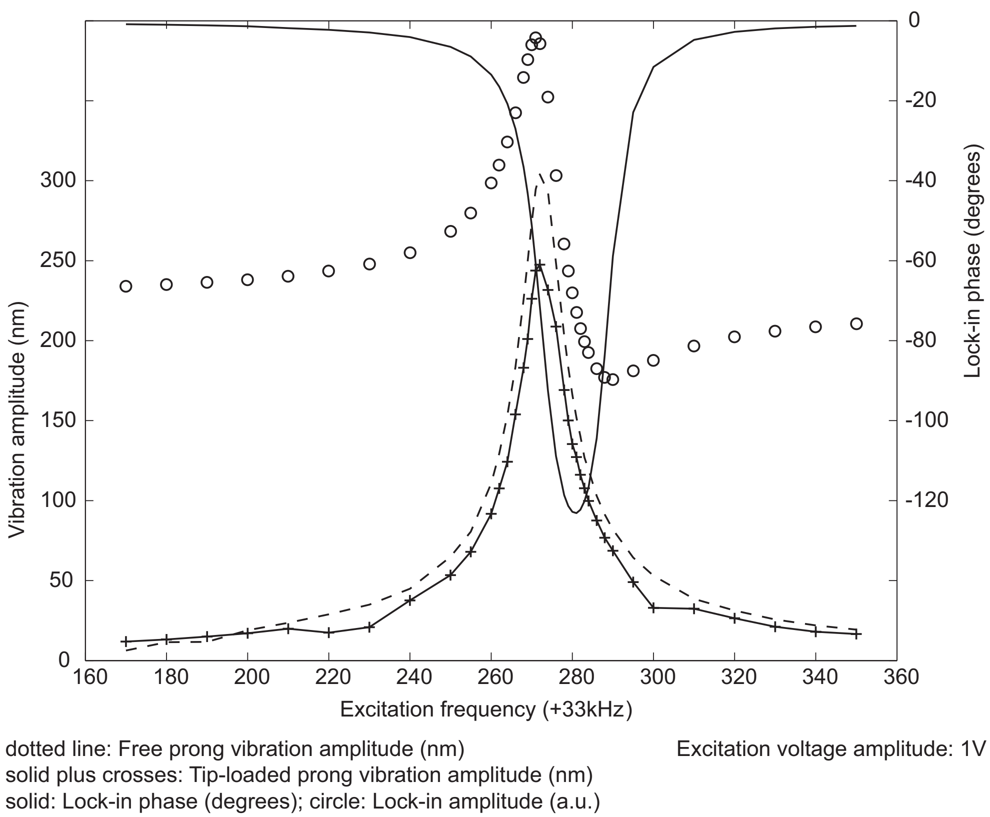

Figure 8. Electric and vibration characteristic of tip-loaded tuning-fork around resonance.

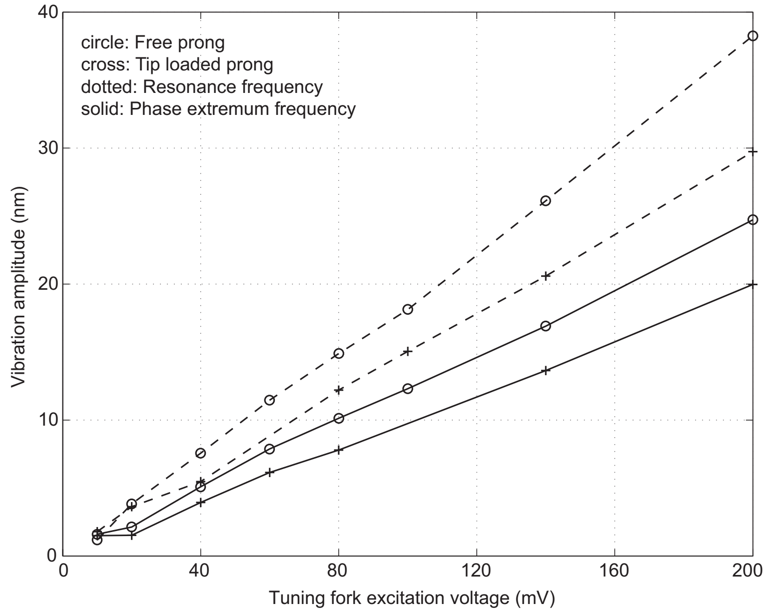

Figure 9. Calibration of the tuning fork vibration amplitude versus excitation voltage. Free and tip-loaded prongs are represented at two different frequencies, i.e. at resonance extremum and at phase shift extremum.

4. CONCLUSION

This paper reports on a new method for in-plane position and orientation measurement. By using a stroboscopic illumination and a low cost vision system, we were able to measure the vibration amplitude of tuning fork prong ends. The latter were prepared by milling a two dimensional set of dots by focused ion beam. The method is effectively based on the phase analysis of a periodic pattern stuck on the object and producing a high contrast in the object image. Image correlation allows the removal of phase ambiguities and the unambiguous determination of position and orientation. Resolutions achieved are in the range of nanometer for the position and of a few 10^{-4}radian for orientation. The method was successfully applied to a near field microscope based on shear-force control of the tip-sample distance. Although the measurement is not performed on the terminal edge of the tip, attenuations due to shear-force interactions were observed and measured.

The proposed method has the drawback of requiring a sample preparation. However, it provides independent position and orientation measurement with a high resolution by using a standard vision system and without the requirement of a scientific grade image sensor. The latter could of course be used and would allow resolution improvements thanks to noise reduction. the stroboscopic illumination allows also to set the vibration of interest onto a low frequency carrier and therefore to extract the pertinent information from main of external disturbances by suitable Fourier filtering. The characterization of MEMS actuators would be another field of application of the method and may propose a convenient alternative to known interferometry methods.

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