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Submicronic Optomechanical Imaging of Tuning Fork Oscillating in Picture-Plane Object

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Abstract:

In this work we present a stroboscopic imaging technique coupled with a CCD camera and multichannel lock-in detection. This technique is applied to a quartz tuning fork micromechanical system oscillating parallel to the image plane, with submicronic amplitude. The aim is both to demonstrate the possibility of observing in 2D this movement in a non-destructive way and to measure its amplitude. This technique allows obtaining two-dimensional full-field images of both amplitude and phase of oscillation by doing just one acquisition.The interest of such an instrument is particularly when the oscillating sample makes its movements in the same plane as that of the image one, or more precisely when according to different constraints it is more easier to install the sample so that its movement occurs in the same plane as that of the image one. This is the case of accelerometers and quartz tuning fork oscillators.

Keywords: Sub-micrometric oscillations, imaging, tuning fork, lock-in detection.

I. Introduction

Metrology imaging of oscillating microsystems devices is of increasing importance if only to follow the evolution of these devices type. Among those devices which justify developing dedicated control instruments, examples include quartztuning fork oscillators and accelerometers. Some devicesthemselves partly require the optical configuration that must be the instrument.

For example, in the case of the quartz tuning fork we have the choice of positioning the device with his arms oscillating perpendicularly to the image plane orpositioning it with his arms oscillating in parallel plane of the image one. In the first case an interferometer based microscopecan easily do such measurement. Such instrument was originally having been developed for two different applications;the first application was to measure oscillations magnitude of micro-cantilevers [1,2,3,4] and the second one was to measure the overpressure induced by a high frequency transducer in clear media[5,2]. Switching between the two applications requires only few changes. This instrumentcan be adapted easily in order to measure the amplitude of oscillations of quartz tuning fork devices disposed perpendicularly to the image plane.

Otherwise it may impose its-own.That is to say that the oscillations of the device must be in the same plane as that of the image one. For example in the case of quartz tuning fork, this configuration is justified by the need to observe the flat part of an arm. Or even simply it is also the case whenthe device type itself requires this configuration which is the case of the accelerometer device type which must keep partially its packaging while removing the top to create a dedicated window for metrology purpose.In that case it would be almost imperative to place the device that its movement occurs in the same plane than the image one.

We present here a novel instrument scheme allowing making optical measurements of oscillationsoccurringin paralleltothepicture plane observedbyaCCD camera. The instrumentperforms a 2D full-field image of submicronic oscillation amplitude in a single acquisition. We use a stroboscopic optical configuration which is coupled to a CCD synchronousdetection[2].The method was demonstrated by using a R26 Raltron™piezoelectric quartz tuning fork device such as a sample. This kind of device usedoriginallyforthedevelopment of digital electronics systems has drawn the attention of many researchers and hasseenitsusedivertedtheselastyearsinother domains such as atomic force microscopy (AFM)[6,7], metrological scanning probe microscope (mSPM)[8], or in monitoring of the physical properties of liquids media[9].

II. Theoretical measurement

To explain the principle of such a measurement, we first consider the ideal case, i.e. in the absence of problems related to the optical system diffusion on the one hand, and assuming a sample with perfect edges. The principle (Cf. Fig. 1-a& Fig. 1-b)is based onpixel whose image on the plane object is confused with the edge of the sample, its width l_{obj} in this plane will depend on both its physical width (in the CCD plane) and the two focal objectives. When $l_{obj}>>a$ (*a:* is the sampleamplitudeoscillation). In the simple case when the camera acquires only two imagesS_0 and S_1, each one corresponding to a half-period of oscillation, and assuming that these images correspond to the two extreme positions of the oscillating sample, we can expect that all pixels observing the sample edge measure a variation of intensity due itself to the variation of the reflecting surface caused by the movement.Levels of S_0 and $S_1$are between values 0 and 1, if we measure a difference signal $|S_0-S_1|$ of 0.02 whichimplies that the peak-to-peak movement of 2% of the width of the pixel in the objectplane.And due to the weakness of the amplitude of movement (compared to the pixel width in the objectplane), theadvantage of using a lock-in detection is justified by the weakness of the resulting modulation of light.

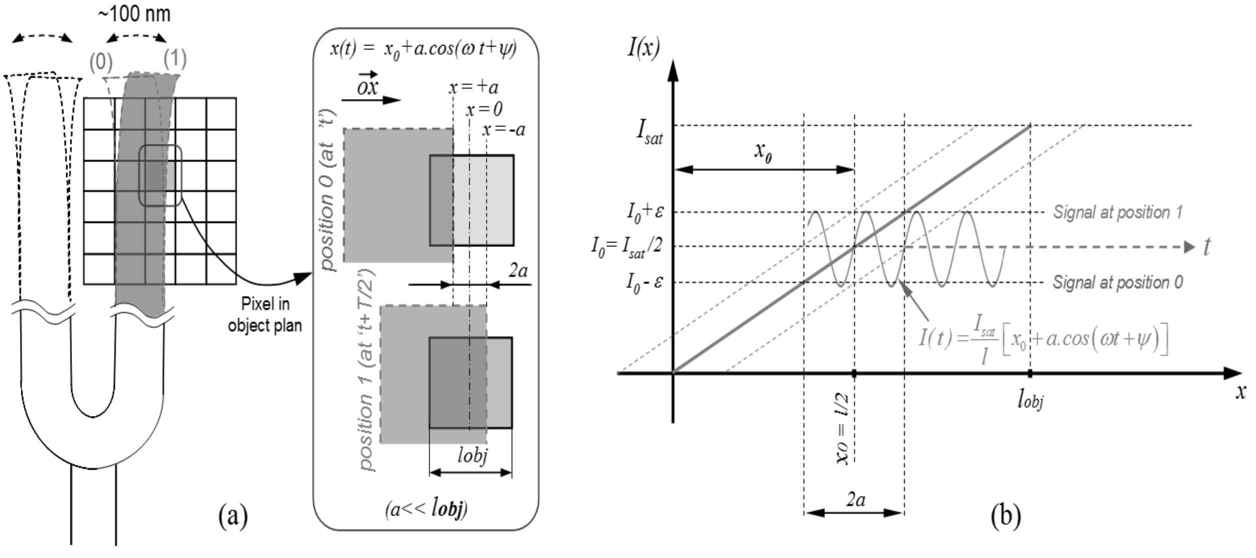

Fig.1: Principle of measurement; (a) Shows reflecting edge sample and pixel image in the same plane of object.

(b) Shows the theoretical effect of the edge sample oscillation on the pixel light intensity.

In an environment dominated essentially by the shot noise (by illuminating the camera in near-saturation), and by doing enough accumulations of images, the system is theoretically easily able to measure variations of light intensity in the range of 1/1000. And if in a first case, we doesn't take into account problems related to optics (diffusion...), we can expect to reach a nanometric sensitivity with an optical magnification of only 10 (for a pixel width reduced in the plane object to the order of a micron). It may already be noted that such precision is possible only under certain conditions; to be on the one hand the edge observed sample moving sufficiently reflective and well-defined.And on the other hand, it will take that the amplitude of movement stays low in comparison with the width of the pixel in the object plane.

II.1 Experimentalsetup

In the new implemented optical instrument (Cf. Fig. 2), the light beam supplied by a LED (30mW, 760nm)oriented at 45° to the figure plane,is collimated by an aspherical lens to a polarization splitter cube which allows to reflect a polarized beam (at 45° of the figure plane) to a quarter-wave plate whose usefulness can be explained by the fact that after reflection on the sample the beam coming from the led will cross twice through the quarter-wave plate, then the polarization of the light becomes orthogonal to its initial direction. This avoids that the light is again reflected by the cube to the source. The light beam is then focused on the sample via a 28 mm photographic lens. Sample reflects then the light beam which crosses a second time the 28mm lens, the quarter-wave plate, and the splitter cube.The CCD camera (DALSA CA-D1, 256x256 pixels)coupled with a zoom objective of 28-300mm, finally receives this reflectedlight beam. The light intensity recorded by each pixel depends on the reflective surface of the sample according to its position relative to the pixel. The oscillations of the sample are obtained by exciting electrically a piezoelectric ceramic attached to it, withelectrical sinusoidal signalsupplied by a generator set to 2^{15} Hz, which is the fundamental frequency of the diapason (decline mode) to provide maximum amplitude of the oscillation at the prongsends of the tuning fork sample.

Setting the zoom-lens to a value of 7 gives a width of the image field (in the object plane)L_{obj} = 571$\mu m$and a pixel width L_{pixel} = 2.24μm.

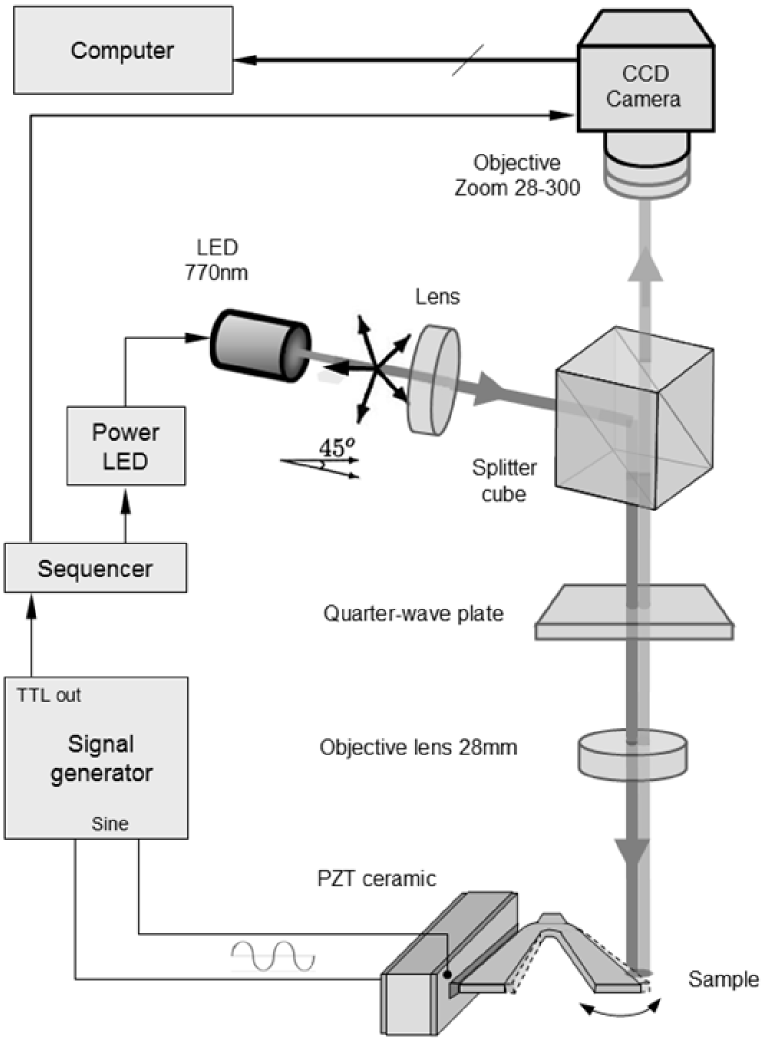

Fig.2: Experimental setup.

II.1.1 Intensity term

We consider the case where the edges of the sample are perfect and the effects of optical diffusion are neglected, and for simplicityas depicted in Figure 1the resting position $x_0$coincides with a half-width of a pixel in the object plane. At x_0 position, I_0 pixel intensity is equal to half of the near-saturation level (The near saturation level is easily obtained from the totally enlightened neighboring pixels).I_{sat}, and changes linearly according to $x_0$position with staying bounded between values 0 and I_{sat}.The sample oscillation creates an alternative component of the intensity (with the same frequency of the oscillation) that will be added to I_0. The term of intensity to the level of a pixel is given by the following equation:

$$I(t)=\frac{I_{sat}}{l}\left(x_0+a\cos(\omega t+\psi)\right) \tag{1}$$

Where $l$is the pixel width in the object plane, and ω is the pulsation of oscillation.

II.1.2 Signal processing analysis

Using thisstroboscopic illumination method by samplinga period of movement with quarters of the period, we get four images S_0, S_1, S_2, and $S_3$for which the lighting is successively shifted by a quarter of a period. Each of these images represents the integral of the light flow received on the quarter of period considered.Where the expression of each image corresponding to quarter-period with $p$index:

$$S_p=\frac{N\,I_{sat}}{l}\int_{p\frac{T}{4}}^{p\frac{T}{4}+\frac{T}{4}}\left(x_0+a\cos(\omega t+\psi)\right)dt \tag{2}$$

Where $l$is the pixel width in the object plane, and N is the number of light pulses.

The expressions of the amplitude and phase are given by:

$$\psi=atg\left[\frac{S_0-S_1-S_2+S_3}{S_0+S_1-S_2-S_3}\right] \tag{3}$$

$$a=\frac{\pi}{2}\times\frac{\sqrt{(S_3-S_1)^2+(S_0-S_2)^2}}{S_0+S_1+S_2+S_3}\times x_0 \tag{4}$$

The amplitude measurement requires gettingthe value of $x_0$which can be easily obtained by doing a simple measurement of I_0. We can then deduce $x_0$from the following relationship:

$$x_0=\frac{I_0}{I_{sat}}\times l$$

II.1.3 Real case; non-perfect edges and optical diffraction and aberration

Two important parameters affecting the quality of such a measurement; the first one is the imperfection of the edge. It depends on the sample itself.The second parameter is related to the diffusion of the optical systemincluding diffraction and optical aberrations phenomena.

One can assume that each part of the edge is made up of several points; each of them is a light source. The image of each source in terms of the CCD for an ideal optical systemand taking into account diffraction would be an Airy pattern.Thus, the image in the CCD plane of an edge area forming a pixel in the sample plane would be then the spatial contribution of all these points' sources in this same area. In practice, this phenomenon corresponds to the fact that the image of the edge spans is in reality several pixels in the CCD plan. In terms of light intensity, and reasoning inone dimension, the image of one pixel of the edge is a rectangle function convoluted by a cardinal-sinesquared.

II.1.4 Practical proportionality (real case)

Because the edges of the sample are positioned parallel to the pixels sides, the influence of their movement should be linearly proportional to these pixels intensity variations. This reasoning can be justified by the fact that the variation ΔS of reflective surface resulting from the subtraction of the two extreme positions of the sample movement, is a rectangle whose width is in the direction of the movement. This rectangle surface ΔS with fixed length and varying in width, will be linearly proportional to its width variation, which provides a linear relationship between the measured ΔS and the movement of the sample. The sample edges imperfections should not influence this linearity as they will be convolved by measuring apparatus optics. This reasoning leads us to propose a method to calibrate our instrument to make it capable of measurements in a dynamic regime. The method consists to assign to the measured intensities the motion amplitude that generates it. We did thatseveral times by changing *a* value of statically simulated movement. The acquisition of two images for each value of '*a'* allows to deduce a curve linking the maximum level of the edge signal to the amplitude of oscillation (Cf.Fig.3). The maximum of signal corresponds to the difference S_0 and S_1 normalized by their sum. These images have been averaged over 15 lines before amplitude calculation.

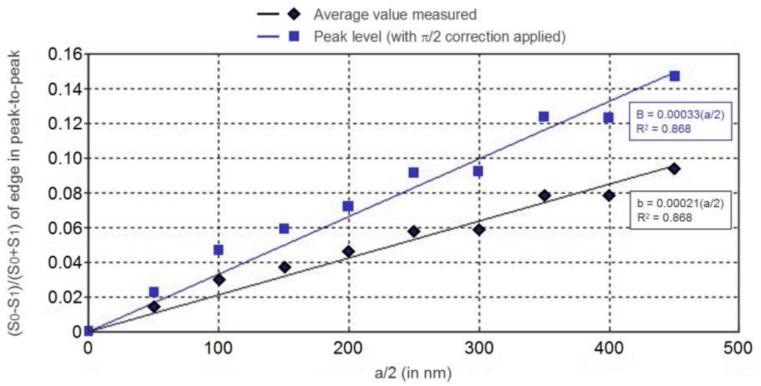

Fig.3: Setup calibration curve linking edge peak-signal levels to the introduced a/2 moving by the actuator.

As in the case of 2 phases acquisition(two images by period of movement), subtractionS_0-S_1 gives intensity corresponding to a peak-to-peak amplitude of motion,the displacement step was then divided by 2 in the curve to simulate peak amplitude in order to be in agreement with a measure in 4 phases acquisition, which provides also a peak of intensity level.In reality, the camera records an average value of half-period of the sample oscillation. Whereas*B* as the peak of this signal and k a constantvalue, the measured average value *b* isgiven by the following relation:

$$b = \langle B.sin(\omega t + k) \rangle_{\frac{T}{2}} = B\int_{0}^{\frac{T}{2}} sin(\omega t + k)dt = \frac{2}{\pi}B \qquad (5)$$

We obtain the following calibration formula giving the peak-to-peak value of amplitude:

$$a_{pk-pk} = 2100 \times \pi \times \mathrm{Max}\left[\frac{\sqrt{(S_0 - S_2)^2 + (S_1 - S_3)^2}}{S_0 + S_1 + S_2 + S_3}\right] \qquad (6)$$

III. Measurements and results

III.1 Amplitude of oscillation measurement

We carried out measurements with this instrument on the R26 Raltronsample. The resonance is reached by measuring the maximum voltage delivered by the electrodes of the Diapason (755 µV at 32769.275 Hz). The measurement was carried out by acquisitions of four images per period of movement by making 100 accumulations of images. The image of amplitude (Fig. 4) shows the signal at the sample arms edges caused by the sampleoscillations. This signal decreases slightly towards the fixed part of the arms (towards the bottom of the image).

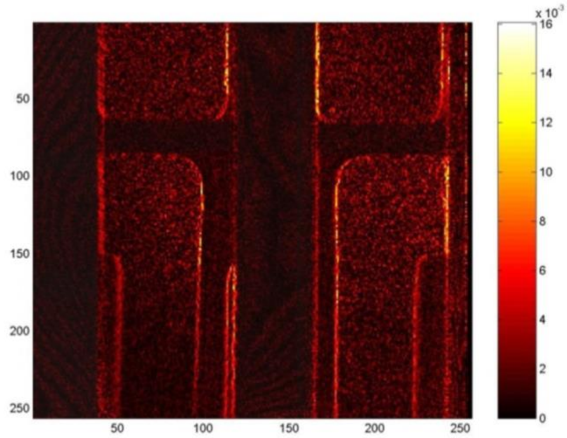

Fig.4: Images amplitude modulation calculated with the 4phases formula.

The measured modulationof light intensity on line 100 gives a value of 1.38%. This allows estimatingthe amplitude of oscillation to approximatively 90 nm which is in accordance with the order of magnitude of such type of sample.

III.2 The information provided by the phase

The phase is calculated using the same formula as in Eq. (7). Figure 5 represents the three phase images corresponding to three frequencies around the resonance. At the top: lower frequency corresponding to an excitation voltage at -3 dB of the resonance voltage. In the middle: in resonance. And at the bottom, resonance: frequency with a voltage level of -3 dB of the resonance. The phase images are used to highlight the oscillation modes of the sample and indicate that the affected pixels are illuminated and unlighted in phase. The measure presented here reveals that the movements of both arms are in opposite directions.

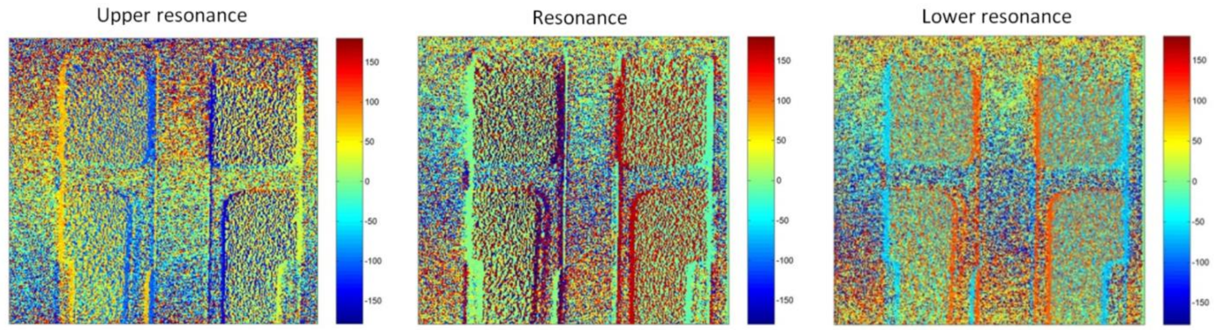

Fig.4: phase modulation images.

IV. Conclusion

The experimental setup presented here has demonstrated the feasibility of a measure of sub-micrometric oscillations occurring in the plane of the image. This configuration is very useful to observe and quantify movements of certain micromechanical systems whose characteristics impose such an optical configuration. This is the case, for example, of accelerometers devices that often require the preservation of their packaging for electrical connections, which requires an observation from the top of the component, often leaving no other choice than using an optical configuration that can observe the movement taking place in parallel to the plane of the image. This is the case of our instrument which coupled with synchronous detection in parallel on all the pixels of the camera, allows to have a global image of the movements of the sample. The measurement obtained from the order of 100nm is very close to that provided by a different assembly used in near field microscopy[6,7]. This is a very encouraging result even if we do not yet fully control the problems related to the diffusion spot regarding the optical part.

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