

Process engineering and failure analysis of MEMS and MOEMS by Digital Holography Microscopy (DHM)

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ABSTRACT

Process engineering and failure analysis of MEMS and MOEMS require static and dynamical characterization of both their in-plane and out of plane response to an excitation. A remarkable characteristic of Digital Holography Microscopes (DHM) is the extremely short acquisition time required to grab the whole information necessary to provide 3D optical topography of the sample: a unique frame grab, without any vertical or lateral scan provides the information over the full field of view. First, it ensures DHM measurements to be insensitive to vibrations. Second, it opens the door to fast dynamical characterization of micro-systems. For periodic movement analysis, DHM can operate in stroboscopic mode with standard cameras. It enables precise characterization up to excitation frequencies of 100 kHz with recovery cycle of 10% simply by triggering properly the camera. Pulsed sources can be used for investigation of higher excitation frequencies. For non periodic movement analysis fast acquisition cameras and postponed treatment are used. DHM are therefore unique and very efficient tool for dynamical characterization of in-plane and out-of-plane response.

In this paper we show the basics of the technology and illustrate process engineering and failure analysis using DHM with an example of in and out of plane characterization of movements of a variable capacitor using the stroboscopic mode of acquisition.

Keywords: Digital Holography Microscopy, Interferometer resolution, MEMS & MOEMS, Dynamical Analysis, Failure Analysis

1. INTRODUCTION

MEMS and MOEMS development, process optimization and quality control require static and dynamic characterization of their shape and movement with an interferometric resolution. From the resonant frequency analysis of structures, such as cantilevers, flexure joints, micro-bridges or membranes, one can evaluate for instance the geometric factor effects, the Young's modulus, the mean residual stress, the effect of air damping, or the study of micro-systems ageing. When developing MEMS and MOEMS, there is a constant need to efficiently compare numerical simulations to the real micro-device movements and to adapt the production process by modifying geometric characteristics.

Optical measurement of the movements of micro-systems is a commonly used method for the characterization of the mechanical properties of micro-systems. Most of the methods provide only a point measurement of the out-of-plane vibrations and a time consuming mechanical translation of the sample or a scan of the beam is needed to obtain the vibration amplitudes on several locations of the micro-device. These measurements are very sensitive to vibrations making full-field measurement techniques, such as stroboscopic systems using phase shifting interferometry (PSI) or Fast Fourier Transform (FFT) analysis of interferograms, highly desirable. Nevertheless, their speed is limited and they are sensitive to vibrations as information from several interferograms taken successively over a relatively long period of time need to be combined.

Digital Holographic Microscopy implemented in off axis configuration allows the retrieval of the full three dimensional information with a nanometric vertical resolution from a single image acquisition. This important feature makes DHM systems a unique tool for MEMS and MOEMS both in and out-of-plane characterization:

- Short acquisition time (down to one microsecond using a standard camera) makes DHM systems insensitive to external vibrations.
- Digital procedures enable correction for any vertical movement between two successive measurements or tilt of the sample associated with ambient vibrations. DHM systems operate without vibration insulation methods, making them a cost effective solution for R&D and for implementation on production lines.
- Real-time measurements (up to 15 fps) can be achieved using standard cameras. Higher rates can be achieved with fast cameras and postponed reconstructions.
- Stroboscopic mode can be used with excitation frequencies up to 100kHz and recovery cycle of 10% (i.e. acquisition time of one microsecond) simply by synchronizing the camera acquisition with the micro-device driving signal to capture the optical topography along the whole movement cycle of the micro device.
- Higher excitation frequencies can be achieved using pulsed sources.

Static and dynamical DHM characterization of in and out-of-plane movement of a micro system will be performed in stroboscopic mode in the frame of this paper.

2. DHM PRINCIPLES

Light interaction with a sample modifies both intensity and phase of the illuminating wave. Any available supports for image recording are sensitive only to intensity. Denis Gabor invented in 1948 a way to encode the phase as an intensity variation: the “hologram”¹. Digital Holographic Microscopy (DHM) implements digitally this powerful concept of holography (Figure 1). With the present performances of computers and the developments of digital cameras, holograms can be numerically interpreted within a tenth of second to provide simultaneously: (1) the phase information, which reveals object surface with vertical resolution below 1° of the wave phase (the nanometer scale for homogeneous samples), and (2) intensity images, as obtained by conventional optical microscope. Both images are defined with a diffraction limited resolution in the transverse (Oxy) plane and are “reconstructed” from the hologram in real time (more than 15 reconstructions per second for 512×512 holograms).

The strength of DHM lies in particular on the use of the so-called off-axis configuration², which enables to retrieve the 3D phase and intensity images of the observed object by numerical reconstruction of a single hologram, which comprises the whole information, and which can be acquired within a few microseconds only.

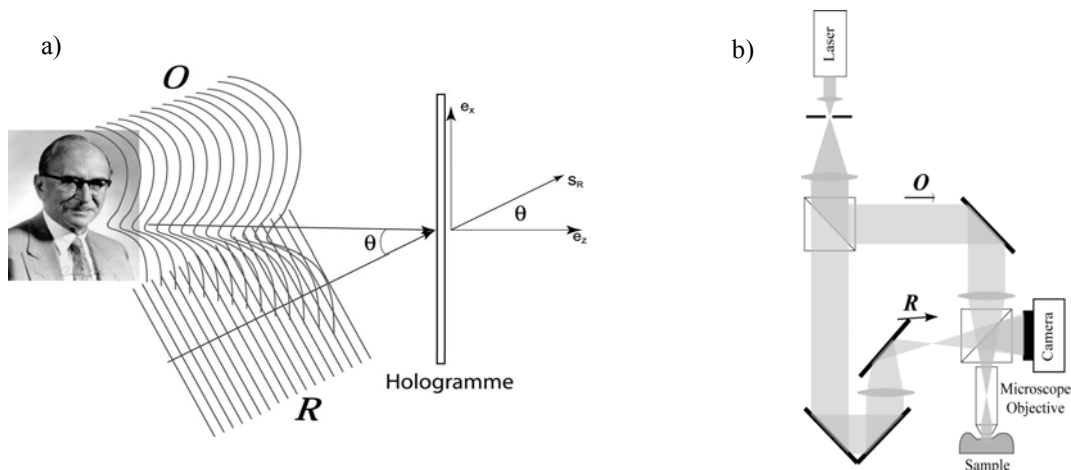


Figure 1: (a) Recording principle of off axis holograms. There are a few degrees (angle θ) between the reference (R) and the object beams (O). This enables to reconstruct the information using a single hologram acquisition. On-axis holography (i.e. $\theta=0$) requires acquisition of several holograms. The portrait is the one of Dennis Gabor, Nobel Price of physics for its discovery of Holography. (b) Optical set up for reflection DHM: the source beam is first separated into two parts: a reference beam and an object beam. The object beam illuminates the sample. The light diffracted by the sample is collected by the microscope objective and is combined with the reference beam to form a hologram on the camera. In this paper, the wavelength of the laser is 682 nanometers.

3. STROBOSCOPIC MEASUREMENTS

The stroboscopic mode is driven by an electronic module composed of an independent microprocessor, developed internally. It enables to trig the camera and include a waveform generator for driving micro systems up to 100 kHz, for voltage ranging between minus and plus 200 Volts. It ensures a perfect synchronization of the acquisition of the images and of the generated output signal. It is connected to the PC by a USB driver and is controlled by the software of the DHM. The monitoring of the sample over its complete cycle is achieved by the acquisition of several holograms (up to 500) over several cycles of the sample, each one being taken at a different position in the cycle (Figure 2). The fact that a single hologram taken in one shot contains the complete 3D information ensures the needed robustness for stroboscopic investigations: insensitivity to external vibrations. On the other side, the very short acquisition time, down to one microsecond, allows instantaneous images of the sample.

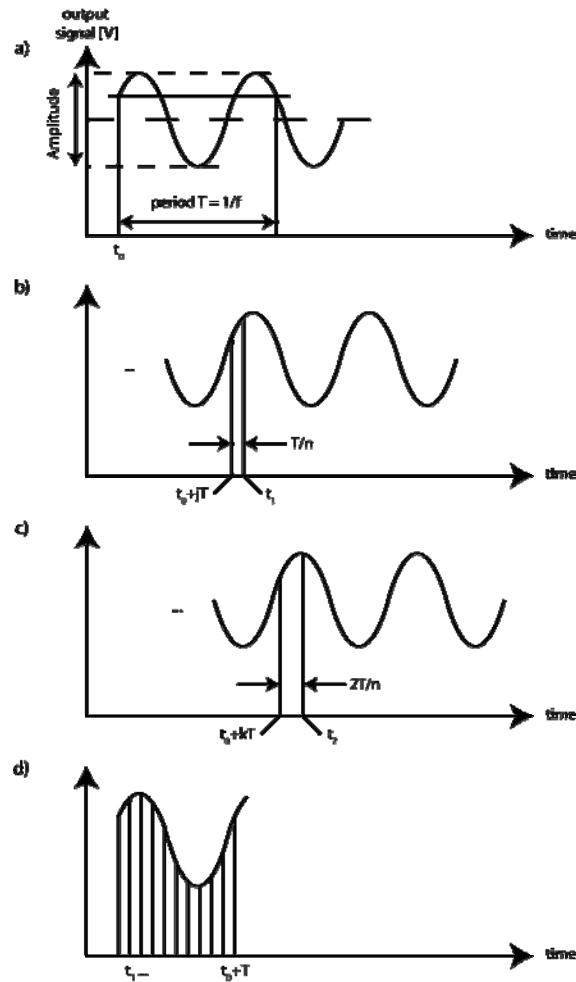
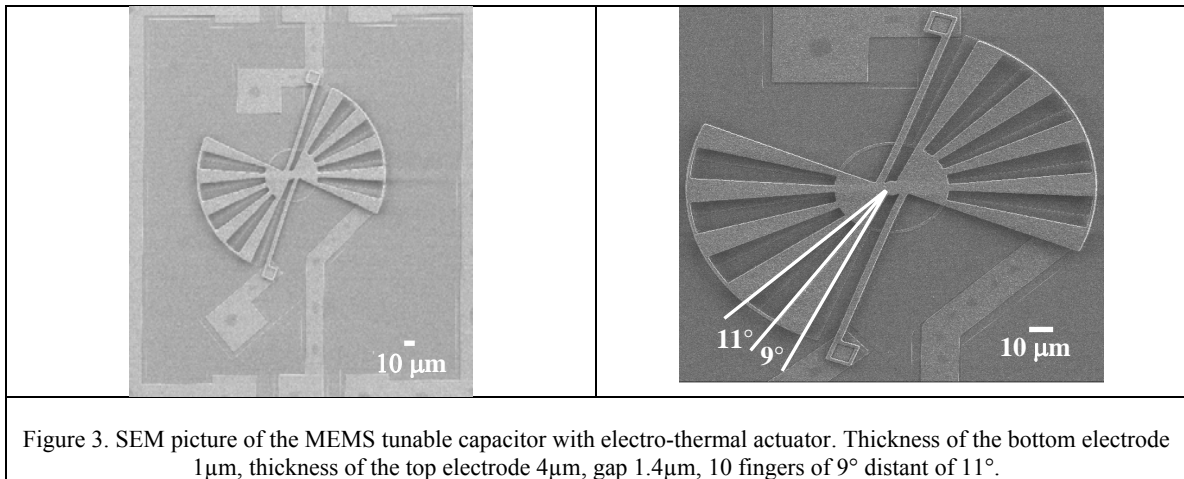


Figure 2 Definition of control settings for stroboscopic mode. Image a) a first hologram is recorded at time t_0 . b) when the system is ready again (that is after time T_{\min} of camera data transfer, image reconstruction, display, analysis, ...) a new hologram is acquired at time $t_1 = t_0 + j \cdot T$, where $j \cdot T > T_{\min}$. c) after a new time T_{\min} a new hologram is acquired at time $t_2 = t_0 + k \cdot T$, where $k \cdot T > 2 \cdot T_{\min}$. d) when n holograms have been acquired, it is then possible to reconstitute the movement of your sample over all its displacement.

4. RESULTS

The schematic of the MEMS characterized in the frame of this paper is presented in figure 3. It is a variable capacitor with fragmented electrodes using arms electro-thermal actuation. It is made of two fragmented electrodes: (i) a bottom fixed electrode and (ii) a top rotationally movable electrode suspended over a $1.4\mu\text{m}$ air gap. Two arms connected on each part of the small central disk structure are used to rotate the top electrode and change the capacitance. When a current passes through the arms, the injected power induces a net thermal expansion of the arm $\Delta l = \alpha l \Delta T$, where α is the thermal expansion, l the length of the beam and ΔT the thermal gradient that creates a moment that rotates the entire structure. The amplification (effective displacement of the outer disk) depends on the dimensions of the actuator and the ratio between the radius of the inner and outer disk. Electro-thermal actuators with various dimensions have been designed. The case study presented here has the following geometry of arms: width = $8\mu\text{m}$, length = $200\mu\text{m}$ and thickness = $4\mu\text{m}$.



The MEMS capacitor behavior has been driven in the frame of this paper, with sinusoidal excitation signals with frequencies ranging from 1 Hz to 100 kHz and voltage from 1 to 1.8 Volts. Although it can be operated up to several GHz, the measurements carried out have enabled a full understanding of its static and dynamical behavior. Two main ranges of operation can be distinguished. For low frequencies, the mechanical movement is function of both the amplitude and frequency of the driving signal. As the frequency increases, the amplitude of the rotation decreases. Above 2.7 kHz, the response time of the structure is probably longer than the excitation frequencies. The position angle of the suspended electrode is apparently only sensitive to the amplitude of the excitation voltage. In this paper, we focused on the most complex case of the micro structure dynamics, i.e. low frequencies. All the measurements presented in this paper have performed with sinusoidal driving signal at 50Hz, centered at 0V. The amplitude of the signal is defined as its the peak to peak value.

The capacity of the micro device is in particular function of the relative distance between the fixed and the moving electrodes. It is mainly characterized by 3 geometrical parameters: (1) the vertical displacement, (2) the rotating angle, and (3) the possible tilt of the suspended structure. Those three parameters have been measured by a DHM configured in reflection and operating in stroboscopic mode to sample 50 measurements along the sinusoidal excitation period.

Figure 4a and 4b show the intensity and respectively the wrapped phase DHM images of the capacitor. As the surface of the suspended electrode is rather rough ($R_a = 24\text{nm}$, $R_t = 156\text{nm}$), phase images have been filtered in the Fourier plane to smooth the surface and to make the measurements less sensitive to surface roughness. Figure 4c shows a typical example of filtered phase measurement.

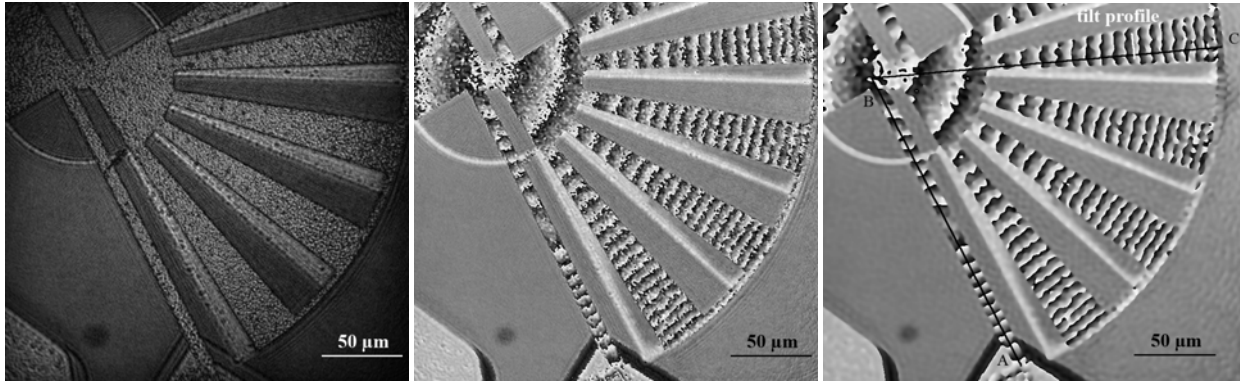


Figure 4: (a) DHM intensity measurement of the MEMS capacitor, (b) Wrapped DHM phase measurement of the MEMS capacitor, and (c) Wrapped filtered DHM phase measurement of the MEMS capacitor. The profile measurement has been extracted along the black line ABC, and the tilt has been evaluated along the white line.

As any phase image, figures 4b and c exhibit so-called “phase jumps”. Between two successive phase jumps (i.e. each time the phase drop from $+180^\circ$ to -180° , represented in white and respectively black on the figure), the difference in height is half of the operating wavelength, i.e. 682.5 nm in our set up. As a result, a phase image does not allow us to resolve steps higher than 341.25 nanometers. To investigate changes in height of the suspended structure, the solution is to choose path along continuous surfaces. For instance, to measure changes of height of point C, we draw a profile from a point having a fixed height (Point A) to the point C, passing through the center of the structure (point B).

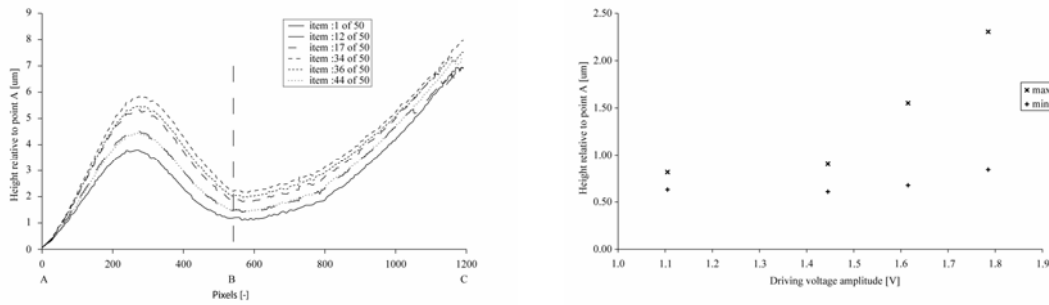


Figure 5: (a) Height profile along the ABC section as a response to signal amplitude of 1.785V for six of the 50 positions measured along the sinus period (b) Minimum and maximum height difference between the fixed point A and the point B on the suspended electrode for four different driving signal amplitude.

For instance, figure 5a shows six profiles, over the 50 measured for the full sinus period, for driving signal amplitude of 1.785V. Figure 5b shows the minimum and maximum height difference between the fixed point A and the point B for four different sinus amplitudes. For amplitudes smaller than 1.5 V, the micro system retrieves its original position. The heat induced by the current can be completely dissipated in the structure. The height changes do not exceed a few hundred of nanometers. For signal amplitude larger than 1.5V, the device does not retrieve its original position and the change of height of the suspended structure exceeds 2 microns. Minimum and maximum heights are not linear functions of the driving signal amplitude.

The rotation angle of the structure can be characterized on both DHM phase and intensity. The center of rotation is defined by the intersection of the prolongation of the finger borders, and the movement is characterized comparing to the fixed electrodes. Figure 5a superposes the minimal and maximum rotation angles for driving signal amplitude of 1.785 V, and figure 5b reports the maximum and minimum angles of rotation for four different driving voltages. The

driving amplitude controls the rotation amplitude.

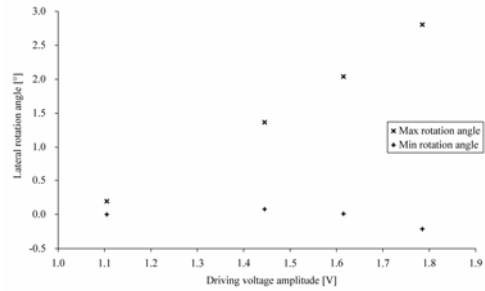
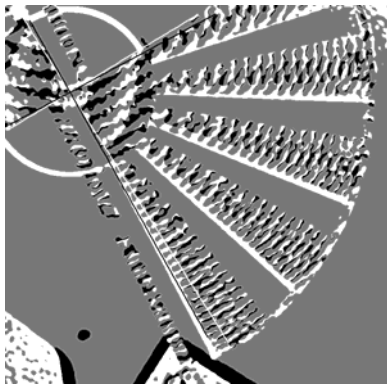


Figure 6. a) Superposition of the phase image for the minimum and maximum rotation angles obtained with a driving signal amplitude of 1.785V. The white lines delimit the edges at minimum angle position, the black ones at maximum. b) Minimum and maximum angles reached for four different driving signal amplitude.

For signal amplitudes below 1.5 V, the deflection angle seems to exhibit a linear response as a function of the voltage amplitude. For larger amplitudes, the maximum angle increase almost linearly with the driving signal amplitude, but the minimum rotation angle decreases. The inertia of the system may explain this fact.

The tilt of the structure has been determined by extracting out of the phase measurement profiles perpendicular to the symmetrical axis of the fingers (See figure 4c). To minimize the measurement uncertainties associated with the roughness, a least mean square fit is performed to determine the straight line the most representative of the profile. The angle of this line is reported as the tilt of the finger. The coordinates of the left side of the profiles have been set to zero to allow comparison of the tilt as a function of various driving signals on a same figure.

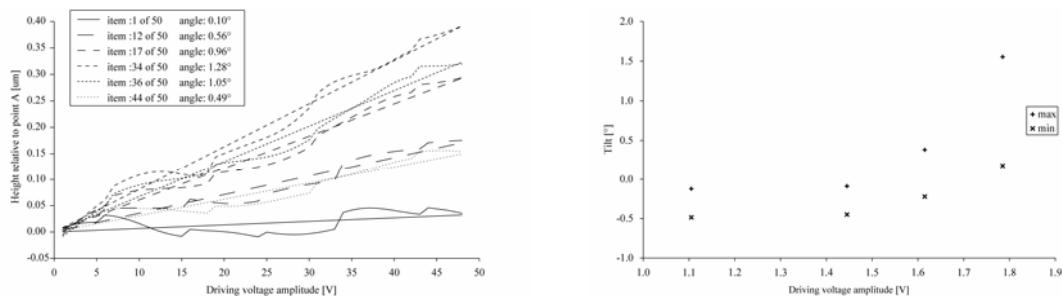


Figure 7: (a) Tilt of the horizontal finger of the suspended electrode at various positions along a sinusoidal driving signal of 1.785V period. For shake of illustration, only six profiles over the 50 measured are drawn (b) Minimum and maximum tilts of the finger of the suspended electrode for four different driving signal amplitude.

For driving signal amplitude below 1.5 V, the minimum and maximum tilts are not strongly function of the amplitude. For larger amplitudes, the device does not retrieve its original position and the tilt starts to be notably function of the signal amplitude. Both minimum and maximum values are not a linear function of the sinus amplitude.

5. CONCLUSIONS

DHM operating in off-axis configuration are fast and robust instruments to investigate MEMS and MOEMS static topography and dynamics. One of their main advantages is that they provide 3D optical topography of the sample from a single acquisition, without any scanning mechanism. This paper demonstrates a dynamical 3D characterization of in-plane and out-of-plane movements of the MEMS capacitor. By characterizing the relative displacement and the tilt of

the electrodes, the analysis carried out enables a good understanding of the capacity's mechanical response to the driving voltage and of the thermal dissipation issues. It enables to define several behavior domains as a function of the voltage amplitude for a fixed frequency. Similar analysis can be performed as a function of the frequency in order to complete the characterization of the system. Future measurements will investigate the relaxation time of the MEMS capacitor, its behavior at GHz frequencies and aging.

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