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Development of dynamic 3-D surface profilometry using stroboscopic interferometric measurement and vertical scanning techniques

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Abstract. The main objective of this technical advance is to provide a single optical interferometric framework and methodology to be capable of delivering both nano-scale static and dynamic surface profilometry. Microscopic interferometry is a powerful technique for static and dynamic characterization of micro (opto) electromechanical systems (M (O) EMS). In view of this need, a microscopic prototype based on white-light stroboscopic interferometry and the white light vertical scanning principle, was developed to achieve dynamic full-field profilometry and characterization of MEMS devices. The system primarily consists of an optical microscope, on which a Mirau interferometric objective embedded with a piezoelectric vertical translator, a high-power LED light module with dual operation modes and light synchronizing electronics unit are integrated. A micro cantilever beam used in AFM was measured to verify the system capability in accurate characterization of dynamic behaviours of the device. The full-field second-mode vibration at a vibratory frequency of 68.60 kHz can be fully characterized and 3-5 nm of vertical measurement resolution as well as tens of micrometers of vertical measurement range can be easily achieved.

1. Introduction

As micro-electromechanical systems (MEMS) devices move rapidly towards commercialization, the issue of accurate dynamic characterization has emerged as a major challenge in design and fabrication. The design, performances and reliability of MEMS and micro-opto-electromechanical systems (MOEMS) critically depend on the control of whole technology and especially on the knowledge and control of the mechanical behaviour of materials and micromechanical devices [1][2]. Characterization of the real mechanical behaviour of MEMS is essentially required since the theoretical simulation may be impractical due to possible dimensional imperfections, unexpected effects from inherent stress gradients, unpredictable real boundary conditions and damping mechanisms.

Heterodyne laser vibrometers based on the laser Doppler effect, extensively used for MEMS vibration spectra measurements, typically have a detection limit below 10 pm in a frequency bandwidth of a few MHz with the capability of being unsensitive to environmental noises and good for out-of-plane measurement both on smooth and rough surfaces [2][3]. To enhance the scanning efficiency, optical microscopic interferometry, digital holography (DH) and electronic speckle pattern interferometry (ESPI) can all be applied to out-of-plane vibration measurements of MEMS, based on either time averaging or stroboscopic techniques. Time-averaged interferometry with a fringe contrast function can perform a quantitative analysis of the interference pattern contrast to obtain vibration mode shapes, but are only suitable for low vibration frequency measurement. To resolve this issue, time-resolved stroboscopic measurements using either white light or single wavelength LED light or pulsed laser, can be deployed for full-field interferometric techniques for 2D or 3D measurements of vibration mode shapes with a theoretical measurement bandwidth up to 2 MHz [4][5]. Thus, the major effort aims to develop a microscopic prototype based on white-light stroboscopic interferometry using vertical scanning principles, in allowing full-field 3-D static and dynamic measurements at a few tens of micrometers range and high bandwidth response.

2. System set-up

The optical system was primarily established on a white light Mirau-type optical interferometer. Shown in Figure 1, the developed system mainly consists of an optical microscope, in which a Mirau interferometric objective being integrated with a PI piezoelectric vertical translator is deployed as the core of the system. The piezoelectric transducer being embedded capacitive sensors for close loop control has a 100 μm vertical translation range and a nanometric resolution. The system was also equipped with a single LED (NSPW 300BS) with a maximum power output of 3 watts, capable of being driven in pulsed or continuous wave modes when incorporating with the light control electronics. The light spectrum of the applied LED and its hardware module can be illustrated in Figure 2 and 3, respectively. This arrangement enables a dual mode measurement capability in a single interferometer, where the continuous white light source can be applied for static surface profilometry while the stroboscopic light source is utilized for dynamic vibratory measurements. A 5V square voltage with a duty cycle of 2% is used to drive the electronics of the stroboscopic LED. The MEMS test sample is actuated by applying a sinusoidal voltage being generating from a 20 MHz function waveform generator. The two driving signals mentioned above are accurately synchronized with an adjustable phase delay, in order to generate frozen interferograms. The incident light from the light source module is collimated by a set of optical lenses for producing a parallel white light beam that illuminates the measured surface and reference mirror. The whole system is mounted on a vibration-isolation optical table and placed in an environmentally controlled space to minimize the influences of external vibrations and disturbances.

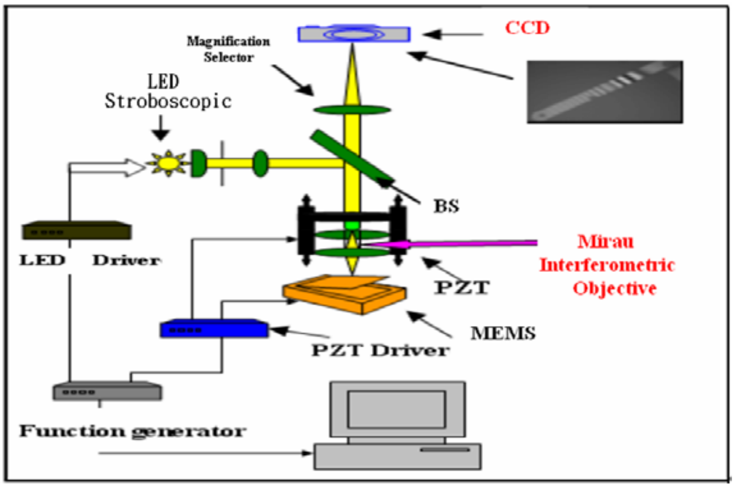


Figure 1. Schematic diagram of the System Set-up

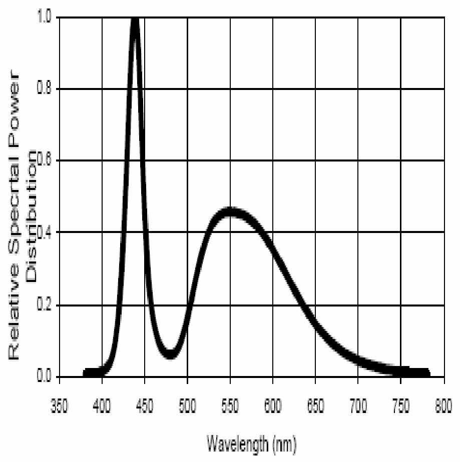


Figure 2. The light spectrum of the LED light source

3. Stroboscopic vibration measurements analysis

The detected intensity in the white light interferogram for an optical path difference between the two optical arms can be expressed as follows [4]:

$$I(x,y) = I_o[1 + C(z)\cos(4\pi\, z/\lambda_{mc} + \Delta\varphi)\ ] \tag{1}$$

where, I_0 is the background intensity, λ_{mc} is the apparent mean source wavelength; $\Delta\varphi$ is the local reflection phase shift difference; and $C(z)$ = the global contrast function.

The above equation only suits the case when the continuous LED light source is applied. For stroboscopic measurements, the sample is illuminated during a light pulsed time δT. Assuming $\sin(n\,\delta T/T)/(n\delta T/T) \cong 1$ for all harmonics (T is the vibratory period), the intensity detected in stroboscopic measurements can be described as follows:

$$I\left(x,y\right) = N\ \delta T\ I_0\left[1 + C\left(z_0 + \Delta\varphi + a\sin(\omega\ t_0 + \phi_1)\right)\cos\left(\frac{4\pi}{\lambda_{mc}}z_0 + \Delta\varphi + \frac{4\pi}{\lambda_{mc}}a\sin(\omega\ t_0 + \phi_1)\right)\right] \tag{2}$$

where, N is the number of vibration cycles; T_0 is the acquisition time of image; t_0 is the phase delay between the light pulse and the PZT driving signal; a is the vibration amplitude and z_0 is the mean vibratory position.

Thus, when considering low vibration amplitudes and short light pulses such as $\sin(n\omega\delta T/2)/(n\omega\delta T/2) \approx 1$, the detected intensity of stroboscopic inteferograms being accumulated N times can be expressed by:

$$I(x,y) = N\int_{t_0-\delta T/2}^{t_0+\delta T/2} I(x,y,t)dt \cong\ N\delta T I_0\left[1 + C(Z_0)\cos\left(\frac{4\pi}{\lambda_{mc}}z_0 + \frac{4\pi}{\lambda_{mc}}a\sin\left(\omega t_0 + \phi_1\right) + \Delta\varphi\right)\right] \tag{3}$$

The above intensity is similar to the one for static measurement when the interferometric image is frozen using stroboscopic light. Figure 4 illustrates an interferogram example of measuring AFM probe cantilever beams, in which the image contrast is as good as the one for its static mode.

Figure 3. The developed stroboscopic LED light module

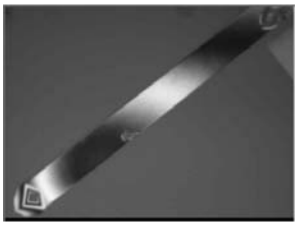
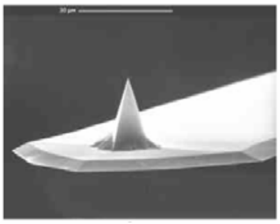


Figure 4. The white-light stroboscopic interferogram image of measuring an AFM probe cantilever beam

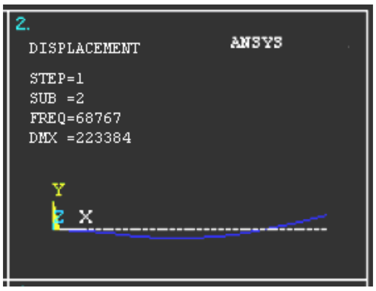
4. Experimental results and discussion

A contact-mode AFM cantilever microbeam was taken as an example for measuring its static and dynamic surface profiles. The micro cantilever was fabricated by Nanoprobe Corp. and its detailed material specification can be referred to Figure 5. A theoretical simulation on the beam dynamic analysis was performed using ANSYS software and the result of its second resonance mode was chosen as an example (shown in Figure 6), in which its natural frequencies were predicted as 68.767 kHz. The actual natural frequency (68.60 kHz) was measured by a laser Doppler interferometer and identified to be slightly less than the predicted one. Following this, using the developed white light interferometric scanning method, the result of its static 3-D surface profile was first obtained for the initial beam status evaluation. Illustrated in Figure 7, it shows that the maximum deflection of the cantilever beam was less than 1 micrometer, which indicates the beam was orientated of a relatively flat level. For the dynamic measurement, a 20Vpp sinusoidal voltage with a frequency of the second vibration mode was applied to the PZT driver and a 2% duty cycle (illustrated in Figure 8) was used for the stroboscopic measurement. Using the stroboscopic measurement method, a series of sequential vibratory shapes of the second resonance mode were obtained and four of them are shown in Figure 9. It was confirmed that its maximum amplitude was up to ±3μm, which coincides with the ANSYS results. The detection limit and resolution were both estimated to about 5 nm and 1 nm, respectively.



Technical Data	Typical Value	Typical Range	Specified Values
Thickness /μm	2	1.5 - 2.5	1.0 - 3.0
Mean Width /μm	50	45 - 55	42.5 - 57.5
Length /μm	450	445 - 455	440 - 460
Force Constant /(N/m)	0.2	0.07 - 0.4	0.02 - 0.77
Resonance Frequency /kHz	13	9 - 17	6 - 21

Figure 5. The dimension specification and physical parts of the tested AFM cantilever beam



```
2
DISPLACEMENT          ANSYS

STEP=1
SUB =2
FREQ=68767
DMX =223384
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Figure 6. The simulation results of the second resonance mode of the test sample using ANSYS software

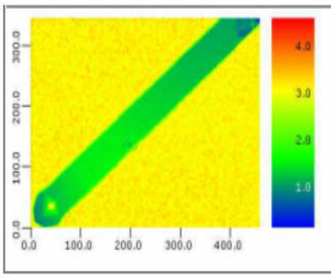

Figure 7. The static 3-D profile of the cantilever beam

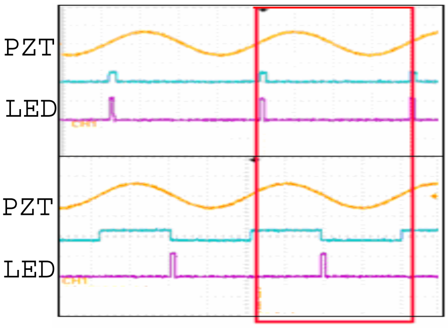

Figure 8. The LED and PZT driving signals are accurately synchronized with an adjustable

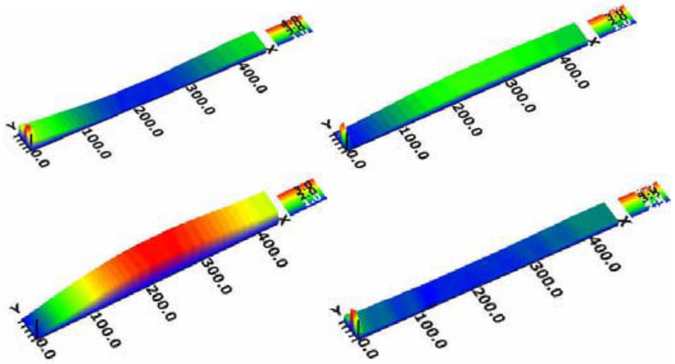

Figure 9. The dynamic 3-D profile measurement results of the tested cantilever beam at the second resonance mode

5. Conclusions

A dynamic surface profilometry based on white light interferometric scanning with a stroboscopic LED light was successfully developed for the dynamic characterization of M(O)MES devices. From the experimental results, it shows that the developed method is well suited for characterizing devices having a discontinuous geometry and a large shape deformation of more than a few tens of micrometers. The main achievement of this technical advance is to provide a single optical interferometric system and methodology for delivering both nano-scale static and dynamic surface profilometry.

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