High-Bandwidth Dynamic Full-Field Profilometry for Nano-Scale Characterization of MEMS

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Abstract. The article describes an innovative optical interferometric methodology to delivery dynamic surface profilometry with a measurement bandwidth up to 10MHz or higher and a vertical resolution up to 1 nm. Previous work using stroboscopic microscopic interferometry for dynamic characterization of micro (opto)electromechanical systems (M(O)EMS) has been limited in measurement bandwidth mainly within a couple of MHz. For high resonant mode analysis, the stroboscopic light pulse is insufficiently short to capture the moving fringes from dynamic motion of the detected structure. In view of this need, a microscopic prototype based on white-light stroboscopic interferometry with an innovative light superposition strategy was developed to achieve dynamic full-field profilometry with a high measurement bandwidth up to 10MHz or higher. 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 characterisation of dynamic behaviours of the device. The full-field seventh-mode vibration at a vibratory frequency of 3.7MHz can be fully characterized and nano-scale vertical measurement resolution as well as tens micrometers of vertical measurement range can be performed.

1. Introduction
This article introduces an innovative dynamic 3-D full-field surface profilometry with high-bandwidth measurement capability for nano-scale characterization of Micro-Electro-Mechanical-Systems (MEMS). MEMS possess system functionality essentially replying on the dynamic displacement properties of the microstructure and accurate characterization. This kind of characterization especially requires comprehensive knowledge of the vibration behaviour of the MEMS. 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]. Characterization of the real mechanical behaviour of MEMS is essentially required since the theoretical simulation may be impractical due to possible dimensional imperfections and unexpected effects from material properties [2].
Time-resolved stroboscopic measurements using either superluminescent LED light (single wavelength or white light) or short-pulsed laser have been effectively employed for dynamic full-field interferometric measurement and resonant mode analysis of MEMS devices. Although time-averaged interferometry with a fringe contrast function can perform a quantitative analysis of the interference pattern contrast to obtain vibration mode shapes, it only suits for vibration measurement with a low measurement bandwidth. Most of the methods or techniques \[3,4\] being developed have a limit in measurement bandwidth, up to a couple of MHz. This is mainly caused by the incapability of time-resolved stroboscopic light in capturing the moving interferometric fringes. Undesired ambiguity of blurring fringes brings difficulties in dealing with phase manipulation for shape reconstruction.

To resolve the above limitation, a novel light superposition principle was developed to superpose multiple light sources into a strobed light having an extremely short width, less than few tenths nanoseconds. The approach is developed to ensure a short-pulsed strobed LED light for freezing the interferogram on the surface of a vibratory tested object. With this short light pulse, the measurement bandwidth can be theoretically increased to 10MHz or more. Meanwhile, to ensure consistent operation of image acquisition of CCD camera, the same pulse signal is applied to the external trigger terminal of the CCD. A contact-mode AFM cantilever microbeam was taken as an example for measuring its full-field vibratory surface profiles at a high vibratory frequency.

2. System set-up and generation of the superposed stroboscopic light

Shown in Figure 1, a Mirau stroboscopic interferometric optical layout was established using a signal synchronization methodology and phase shifting principle. The developed system consists of an optical microscope as the main system structure, a Mirau interferometric objective, a piezoelectric vertical actuator and the stroboscopic light generation module. Two single superluminescent LED (NSPW 300BS) lights with a maximum power output of 6 watts incorporating with the light control electronics, are applied to provide strobed light for clear fringe detection, shown in Figure 2. Both of light-triggering and MEMS-driving signals mentioned above have to be accurately synchronized with an adjustable phase delay \((0\sim2\pi)\), in order to generate frozen interferograms with good image contrast. Most importantly, an extremely short pulse with a duty cycle in 2% of the vibratory cycle used to drive the electronics of the stroboscopic LED is generated using a superposing light principle. Two channels of the LED pulsed light with a Gaussian intensity distribution can be superposed into a new pulsed light with a higher intensity and sharper pulse width. Figure 3 illustrates that an original pulsed light with a pulse width of approximately 85 ns can be transformed into a superposed pulse light with a double light strength and sharper pulse width.

![Figure 1. Schematic diagram of the system set-up.](image-url)
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 in generally as follows:

\[ I(x, y) = I_0 \left[ 1 + C(z) \cos(4\pi \frac{z}{\lambda_{mc}} + \Delta \varphi) \right] \]

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

Assuming the vibratory motion for all harmonics (\( T \) is the vibratory period) is periodic and modulated by a sinusoidal function with vibrating amplitude \( a \) and frequency \( \omega \), the intensity detected in white-light interferometric measurements during the vibratory motion can be described as follows:

\[ I(x, y) = I_0 \left[ 1 + C \left( z_0 + \Delta \varphi + a \sin(\omega t_0 + \phi) \right) \cos \left( \frac{4\pi}{\lambda_{mc}} z_0 + \Delta \varphi + \frac{4\pi}{\lambda_{mc}} a \sin(\omega t_0 + \phi) \right) \right] \]

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

To freeze the moving fringes modelled in above equation and prevent the interferogram from becoming blurring, a strobed light with a short pulse width \( \sigma \) is applied to capture the vibrating fringes. For stroboscopic measurements, the sample is illuminated during a white-light pulsed time \( \delta T \).

The pulsed light generated from the stroboscopic light module can be expressed as follows:

\[ P = P_0 e^{-\sigma^2 / 2 \delta T^2} \]

Where \( P_0 \) is the maximum pulsed light intensity; \( t_0 \) is the mean; \( \delta T \) is the standard deviation, representing the width of the pulsed light.

The detected intensity \( I_s(x, y) \) of the stroboscopic interferometry can be modelled as the convolution between the interferometric light intensity \( I(x, y) \) and the pulsed light \( P \) as follows:

\[ I_s(x, y) = I \ast P = I_0 \left[ 1 + C \left( z_0 + \Delta \varphi + a \sin(\omega t_0 + \phi) \right) \cos \left( \frac{4\pi}{\lambda_{mc}} z_0 + \Delta \varphi + \frac{4\pi}{\lambda_{mc}} a \sin(\omega t_0 + \phi) \right) \right] \ast P_0 e^{-\sigma^2 / 2 \delta T^2} \]

Since the actual detected light intensity of the stroboscopic interferometry is accumulated for \( N \) times, the detected intensity can be further expressed by an integration along a period of detecting time \( T_d \):

\[ I_s(x, y) = \int_0^{T_d} I_s(x, y, t) \, dt \]

\[ = N \int_0^{T_d} I_s(x, y, t) \, dt \]

**Figure 2.** Optical layout of the stroboscopic system.

**Figure 3.** Superposing effects of stroboscopic pulsed light.
Furthermore, when assuming low vibration amplitudes and short light pulses such as \( \delta T / T \lesssim 0.05 \), the detected intensity of stroboscopic interferograms can be approximated and simplified as:

\[
\overline{I}(x, y) \approx N \, \delta T \, I
\]  

(6)

The above intensity is similar to the one for static measurement when the interferometric image is frozen using stroboscopic light. Figure 4 illustrates a stroboscopic interferogram example of measuring AFM probe cantilever beams. The image contrast of the detected stroboscopic light after several time accumulation can be as good as the one for its static mode, shown in Figure 5.

4. Experimental results and discussion

A contact-mode AFM cantilever microbeam was taken as an example for measuring dynamic surface profiles. The micro cantilever was fabricated by Nanoprobe Corp. and its detailed material specification can be referred to Reference [1]. A theoretical simulation on the beam dynamic analysis was performed using ANSYS software and the result of its sixth and seventh resonance mode was chosen as an example, in which its natural frequency was predicted as 3.715 MHz. Their actual natural frequency (3.733MHz) was measured by the developed automatic resonant frequency detection software and identified to be slightly higher than the predicted one. Following this, a 40Vpp sinusoidal voltage with a frequency of the vibration mode was applied to the PZT driver and a 20ns pulsed width light was generated for the stroboscopic measurement. Using the stroboscopic measurement method, the vibratory shape of the resonance mode was obtained and shown in Figure 6. It was confirmed that its maximum amplitude was up to 700nm, which coincides with the ANSYS results. The detection limit and resolution were both estimated to about 5 nm and 1 nm, respectively.

![Fig 4](image)

**Figure 4.** The stroboscopic interferometric light intensity of white light: (a) the interferometric signal of the static measurement; (b) the pulsed light intensity; (c) the signal stroboscopic light intensity of a vibrating AFM tip at 1.003 MHz; and (d) the accumulated light intensity of the strobed light after repeating 5 times.

![Fig 5](image)

**Figure 5.** The white-light stroboscopic Interferogram image of measuring an AFM probe cantilever beam: (a) the applied strobed light pulse and (b) the detected interferogram.
Figure 6. The dynamic 3-D profile measurement results of the tested AFM cantilever beam at the resonance mode of 3.7 MHz: (a) the detected interferometric fringe; (b) the 3D vibratory profile; and (c) the cross profile section.

5. Conclusion
A high-bandwidth dynamic surface profilometry based on white light interferometry with a stroboscopic superposing LED light was successfully developed for the dynamical characterization of M(O)MES devices. From the experimental results, it shows that the developed method is well suited for characterizing devices at a high vibration frequency up to 10 MHz. The full-field 3D vibratory mode at a vibratory frequency of several MHz can be fully characterized and 3–5 nm vertical measurement resolution as well as tens μm of vertical measurement range can be satisfactorily achieved.

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