STUDY ON DEFORMATION OF A MICRO BEAM USING INTERFEROMETRY

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ABSTRACT

An optical Mirau interferometry technique is developed to measure both static and dynamic characteristics of a surface micromachined beam under electrical loads. A standard CCD camera and a high-speed CMOS camera armed with long working distance microscope are utilized to capture the interference fringe patterns under static and dynamic test respectively. Phase distributions are extracted by continuous wavelet transform (CWT) on one image, which possesses the capability of better noise reduction, and thus better solutions for phase retrieve. Another distinguishing characteristic of the methodology is its simplicity including avoiding adding carrier and identifying the phase ambiguity points by directly tracking the inflection points from the unwrapped phase map. Therefore it is suitable for measuring both static and dynamic deformations of MEMS (Micro Electro-Mechanical Systems) structures in real-time. The proposed algorithm is validated, both via computer simulation and real fringe patterns. Both static and dynamic deflections of the micro-beam are obtained. The experimental results demonstrate that the proposed technique is a potential inspection tool for the analysis of fringe patterns and thus for the evaluation of mechanical properties of micro-components.

Introduction

MEMS (Micro Electro-Mechanical Systems) is a rapidly growing field building upon the existing silicon processing infrastructure and techniques to create micro-scale devices or systems. MEMS devices integrate physical, chemical, and even biological process in micro- and millimeter-scale technology packages, which now are emerging as product differentiators in market areas such as automobile, aerospace, electronics instrumentation, industrial process control, appliances, biotechnology, healthcare, office equipment, and telecommunications\cite{1}. With the development of MEMS industrialization, measuring technologies have become one of the important factors of MEMS fabrication, simulation, quality evaluation and control. Characterization of mechanical and dynamic properties, testing capabilities, and experimentally validated high-fidelity predictive modeling are required to assure that the microsystems reliably perform their intend functions. Micro-machined beams are commonly used in MEMS to measure material properties. The measurements of deflection or motion of micro-beams, under static and dynamic load conditions, can be utilized for analyzing some mechanical behaviors by combining them with a finite element model\cite{2-8}.

Microscopic interferometry has been widely applied to measure microstructure’s profile and deflection with a sub-micrometer lateral resolution and a nanometer vertical resolution, and is capable of measuring out-of-plane motion of microstructures. The final 3-D shapes can be readily obtained from the resulting fringe patterns\cite{9-12}. Phase shifting and the Fourier transform method (FTM) are two commonly used techniques for extracting phase distributions from two-dimensional interferometer fringe patterns\cite{13}. For the former, three or more accurately phase-stepped images are needed, and any inaccuracies in the phase stepping will introduce errors in the extracted phase distribution. FTM is a simple and common way to extract phase distribution from an interferogram and can be improved by adjusting the window function and carrier frequency. However, FTM is a global operation that is usually used for the analysis of stationary of a signal, because it has a poor capacity for localizing the signal properties. It is note worthy that a fringe pattern with drastically changing fringe density or direction is not suitable for FTM, because the frequency spectrum of such fringe pattern hinders a band-pass filter to separate the signal from noise. The windowed Fourier transform (Gabor filter), which performs a local analysis on a fringe pattern, can be a solution to the problem. However, we can only obtain the phase with limited precision, which is determined by the size of the window.

Wavelet transform\cite{14} is a technique that decompose a given signal into the components in both time and frequency localization by the multi-resolution analysis. Recently wavelet transform has become an effective tool in optical interferometry. Two-dimensional continuous wavelet transform was developed by Munther A.Gdeisat to eliminating the zero spectrums in FTM\cite{15}. Dursun employed the Morlet wavelet analysis to obtain the phase gradient and the integration of phase gradient in order to retrieve the phase distribution of the projected fringes in 3-D shape measurement\cite{16}. Michel Cherbuliez used wavelet analysis to process live interference patterns\cite{17}. In this paper, Morlet wavelet analysis is employed to extract phase
distribution in spatial domain [18]. Phase extraction is performed by computing the phase at a wavelet ridge. 3-D profile of the micro-beam under a certain voltage is determined by phase unwrapping in spatial domain. The problem of additive constant between lines is solved by the technique of phase unwrapping in the column direction and better results obtained. Due to the nonmonotone features of the fringe patterns, phase ambiguity occurs during the unwrapping procedure, which can be solved by detecting the inflexion points on the unwrapped phase map and reflecting the phase values of subsequent points. In the case of deformation measurement of each point, wrapped phase is obtained in spatial domain and unwrapped phase is achieved by phase unwrapping in time domain.

In this paper Mirau interferometry technique is developed for measuring deformation and corresponding mechanical parameters of a surface micromachined beam under applied voltage (AC and DC). A CCD camera and a high-speed CMOS camera armed with long working distance microscope are utilized to capture the interference fringe pattern that results from recombination of two beams reflected from the optical mirror in the Mirau objective and the micro-beam. Principles of determination unwrapped phase from a nonmonotonic phase distribution by continues wavelet transform (CWT) are discussed in detail. Both simulated and experimental tests are performed to validate its feasibility. Experimental studies on the measurement of the micro-beam’s surface profile and out-of-plane periodic motion are carried out.

**Interferometry**

Although the micro-beam is relatively small as shown in Figure.1, the deformation is still large compared to the wavelength of visible light and thus optical interferometer techniques are applicable to their characterization. The method presented in this paper is based on the Mirau interferometry of light beams of equal path difference, which results in equal thickness.

![Figure.1 Picture of the micro-beam](image)

In order to determine the deflection of the micro-beam the optical phase difference of the fringe pattern must be calculated. The fringe intensity distribution of the interferogram can be described as

\[
I = I_0 \left[ 1 + \gamma \cdot \cos(\phi(x, y)) \right]
\]

where
- \( I \) = intensity recorded by a CCD sensor
- \( I_0 \) = background intensity
- \( \gamma \) = fringe contrast
- \( \phi \) = phase related to the physical quantity being studied

**Continuous wavelet transform (CWT)**

Similar as Fourier transform which represents a signal as a superposition of sine and cosine functions, continuous wavelet transform (CWT) represents a signal in terms of wavelet functions:

\[
W_g(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(x) \cdot \overline{g} \left( \frac{x-b}{a} \right) dx
\]

where
- \( W_g(a,b) \) = CWT coefficient function by a CCD sensor
- \( a \) = scale parameter
- \( b \) = shift parameter
- \( f(x,y) \) = signal
- \( g^* \) = complex conjugate of the basic wavelet function

Since the signal in Eq. (1) is modulated by cosine function, a suitable choice of wavelet function is the well-known complex Morlet wavelet:

\[
M(x) = \exp \left( -\frac{x^2}{2} \right) \exp(j\omega_0x)
\]
where $\omega_0 = $ wavelet frequency

Here $\omega_0 = 2\pi$ is chosen to satisfy the admissibility condition so that the wavelet function is able to remove the negative frequencies as well as to avoid the DC contribution of the signals. There are two methods to obtain the phase: one is by integration of the instantaneous frequency. When this method is used, phase unwrapping is not required. Another way for phase extraction is to compute the phase at a wavelet ridge:

$$\phi(b) = \tan^{-1}\left(\frac{\text{Im} W_f(a_n, b)}{\text{Re} W_f(a_n, b)}\right)$$

(4)

where

- $\text{Re} =$ real and imaginary part of a complex wavelet coefficients
- $\text{Im} =$ imaginary part of a complex wavelet coefficients
- $a_n =$ a scaling on the ridge

Obviously, phase unwrapping cannot be avoided. In this study, the second method is preferred. Since wrapped phase are also needed to calculate the deformation between neighboring images from a series of fringe patterns during the loading process [20].

![Circular fringe patterns](image1)
![Theoretical phase distribution](image2)
![Original calculated phase distribution](image3)

(a) circular fringe patterns    (b) theoretical phase distribution   (c) original calculated phase distribution line by line

(d) a column extracted from (c)   (e) unwrapped phase of (d)   (f) calculate phase by the proposed method

![Simulated case of 2D fringes](image4)

Figure 2 Simulated case of 2D fringes

To avoid large error in CWT at the boundary, intensity variation signal on each pixel is extended at its left- and right-hand edges. Symmetrical or zero padding extension techniques are commonly used in practice. In this study, a linear predictive extrapolation method is selected. The advantage of this extrapolation method is that phase and frequency of intensity variations are maintained. After CWT has been carried out on the extended data, the wavelet coefficients are truncated appropriately.

One method for determining the phase distribution of two-dimensional interferometer fringe patterns proceeds as follows: For each row (or column) of the image, extend the fringe patterns at its left- and right-hand edges, using linear predictive extrapolation. Next, measure the scale at the detected CWT ridge and calculate corresponding phase. Thirdly, unwrap the phase in that row. Then the points which introduce phase ambiguity are identified by tracking the inflexion points on the
unwrapped phase map and detected by Savitzky-Golay differential operator. Subsequently reflect the phase values from these points on. This procedure is applied to each row or column respectively and the resulting phase value is obtained by 2D unwrapping technique and smoothing algorithm.

Figure 2 (a) shows a circular nonmonotone fringe pattern without carrier, and Figure 2 (b) illustrates its corresponding theory value of phase distribution. The proposed method is used to each row and the calculated phase is displayed in Figure 2(c). As can be seen, there exist several jumping lines between rows up to an additive constant. Figure 2 (d) is the phase distribution of a column extracted from Figure 2(c), which exhibits four jumping points which is similar to the 2π jumping phenomenon. Figure 2 (e) shows the unwrapped phase of Figure 2 (d), which solves the problem of phase jumping and greatly improves the smoothness of the phase distribution. This procedure is repeated for each column and the resulted phase distribution of entire image is depicted in Figure 2 (f), which agrees well with the theory values (Figure 2 (b)). The maximum error is less than 4 rad, which demonstrates the feasibility on retrieving 2D phase distribution from 2D nonmonotone fringe pattern using the proposed technique in this paper.

**Experiment**

The proposed measurement system consists of a precision microscope with various components as shown in Fig.3. White light from an illuminating source (a halogen bulb of 150W) is directed by an optical fiber bundle onto a light guide and the output from the light guide is directed on Lens through an interference filter. The monochromatic light with wavelength (640nm) is reflected off a beamsplitter and directed onto a Mirau interference objective. A beam splitter and a reference mirror in the Mirau interference objective are incorporated in the system to produce the necessary reference and object beams, which interfere with one another within the coherence length of the filtered light. To position the specimen accurately, the chip is mounted on a 3-axis translation stage. Loading on the micro-beam is applied by means of a probe station. The resulting interference fringe patterns are captured by a CCD camera or high-speed CMOS camera and stored in a computer.
In this study, the beam is approximately 300μm long, 12μm wide and 2μm thick. The designed electrode and the beam are concentric and of the same size. Electrostatic MEMS devices can be directly excited by a DC power source. When a DC voltage is applied across the two plates of the device, an attractive electrostatic force is created, causing the upper movable electrode (beam) to move downwards toward the lower fixed electrode. Care must be taken in electrostatic actuation of microbeams. For deflections greater than about 1/3 of the gap between the driving electrode and the beam, the device will “slam down”. For inadequately protected devices this slam down can result in catastrophic failure. For measuring nonmonotonic surface profile of micro-beam, interferograms at different voltage are captured ranging from 0v to 60v.

Measurement of dynamic deformation

For the investigation of dynamics in microdevices, standard charge-coupled device (CCD) camera is replaced by a high-speed CMOS camera, which allows an image frequency up to 120 kilohertz frames per second for non-reproducible process. The beam is directly driven by a swept sine source of a function generator. This unit, in its swept mode, is capable of generating a sinusoidal voltage up to 10V in amplitude at discrete frequencies over a specified frequency range. For MEMS devices designed to operate at higher voltage, our system incorporates a high-voltage amplifier, extending the range of available signals to 100V. One main advantage is that the motion of the whole surface, rather than a single point, is measured simultaneously. By comparing the variation of the profiles at different motion phase on one full cycle of a periodic motion, the surface deflection of the structure can be extracted. The procedure is similar to the measurement of static deformation. On the other hand, it is also very valuable for evaluating the out-of-plane of a single point in the surface of the microstructure. If only the out-of-plane motion of a single point is to be evaluated, wrapped phase of the point can be obtained by CWT and then unwrapped by temporal analysis.

![Interferogram and Comparison](image)

(a) interferogram (b) comparison between the proposed method and four-step phase shift (c) 3-D surface profile

![Deformation and Frequency](image)

(d) static deformation results (e) out-of-plane motion of three points (f) spectrum of the dynamic signal of point1

Figure 4 Measurement results of the micro-beam

**Results and discussions**

Measurement of the surface profile of the micro-beam is performed to validate the proposed method. Figure 4. (a) shows an interferogram of the beam using a Mirau 20× interferometric objective. It is seen that a carrier fringe is introduced simultaneously, which should be removed during the fringe analysis process. Figure 4. (b) demonstrates the two cross-sectional profiles of the microbeam obtained by applying CWT and the four-step phase shifting method respectively. The height deviation between the two profiles is no more than 60nm. It is easy to detect the bend at the center of the beam accurately by applying the four-step phase shifting method, but the results are not as smooth as those obtained by CWT. While in the CWT case, the phase noise primarily occurs at the center area. To eliminate such noisy effect, a least-square fitting method is utilized, which exhibits great improvement on the resulting profile. The validity of this method is confirmed by
the results show in Figure 4 (b). Figure 4(c) depicts the initial profile of the micro-beam. This indicates that the initial profile of the beam is a concave surface and residual stress accumulates. For the static test, the voltage ranges from 0v to 60v and back to 0v and the results are shown in Figure 4 (d).

For the dynamic test, a sine wave signal with frequency 2.0Hz and peak-to-peak amplitude 20V is applied to the beam. The frame rate of the high-speed camera is 125 frames per second. Figure 4(e) shows the dynamic deformation of three points obtained by unwrapping in time domain, whose distribution is similar to a sine wave, and the vibration amplitude increases gradually with the increase of distance between the test point and the fixed end. As we all know, when the bias voltage is zero (grounded mass), the frequency of the forces that acting on the beam in such mode is twice of “biased mode”. That is to say driving force in the “grounded” mode will actuate with double frequency regarding to the driving voltage frequency. Figure 4(f) shows the frequency spectrum of the response signal, whose basic frequency is 3.9Hz, almost twice of the driving frequency. These results further demonstrate the effectiveness of the proposed method.

Concluding remarks

This paper is focused on the investigation of a micro beam under applied voltage using the proposed phase extraction method based on continuous wavelet transform and corresponding unwrapping techniques. The method proposed in this study provides a new way for phase extraction on a nonmonotonic interferometry fringe patterns. Both static and dynamic tests are performed by applying a dc and ac voltage across the beam, respectively. Deflections of the beam under different loading conditions are obtained. The experimental results show that the proposed technique is relatively simple and accurate for the determination of nonmonotonic interferometer phase distributions, and provides a potential method for the evaluation of mechanical properties of micro components.

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