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HOLOGRAPHIC INTERFEROMETRY FOR VISUALIZATION OF VIBRATIONS OF MICROMECHANICAL STRUCTURES

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Abstract The optical holography and digital holography methods for visualization of modes of vibrations of micromechanical systems are described. The Denisiuk holography approach and optoelectronic techniques for investigation MEMS with sub-micrometer accuracy, shape and changes in states of deformation of MEMS structures are proposed. Examples of holographic visualization of the vibration of links of MEMS are presented.

Keywords: Digital holography, optical holography, micromechanical systems.

1. Indroduction

Metrological technology is of extreme importance in microelectromechanical systems engineering to ensure functionality and reliability of products. Micromechanical tools are thus needed to provide information on the properties as well as on geometry of microstructures for accurate inspection and characterization of these structures. Recent technological trends based on miniaturization of mechanical, electromechanical, and photonic devices to the microscopic scale have led to the development of microelectromechanical systems (MEMS). Effective development of MEMS components requires the synergism of advanced design, analysis, and fabrication methodologies, and also of quantitative metrology techniques for characterizing their performance, reliability, and integrity during the electronic packaging cycle.

MEMS structures are micron-sized electrical and mechanical mechanisms, typically manufactured using very large-scale integration (VLSI) techniques adapted from those of the microelectronics industry, that are used in sensing and actuation applications. MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components, and microelectronics to the design and construction of integrated electromechanical systems. In recent years, MEMS technologies have been adopted by a number of industries in order to produce micro-scale airbag sensors, pressure and temperature sensors, visual display components, DNA samplers, AFM probe tips, microengines on a chip, etc. Potential applications of MEMS include miniature inertial measurement units for competent munitions and personal navigation, distributed unattended sensors for asset tracking and environment/security surveillance, mass data storage devices, miniature analytical instruments, embedded pressure sensors for passenger car, truck, and aircraft tires, noninvasive biomedical sensors, fiber optic components and networks, distributed aerodynamic controls, and on-demand strength sensors [1-3].

As the capabilities of MEMS structures become more widely recognized, it is also recognized that the biggest obstacle to growth of MEMS applications is the design cycle time, since it depends on tightly coordinated application of advanced design, analysis, manufacturing, and testing tools.

Effective development of MEMS components requires the synergism of advanced computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM) and fabrication methodologies, materials science and technology, and also of effective quantitative testing techniques for characterizing their performance, reliability, and integrity [4]. Testing of MEMS includes measurements of their electrical, optical, and/or mechanical responses to the driving signals and/or environmental/loading conditions. Furthermore, in order to understand mechanics of MEMS and materials used for their fabrication, advanced noninvasive testing methodologies, capable of measuring the shape and changes in states of deformation of MEMS structures and materials subjected to actual operating conditions, are required [2-5].

In this paper, we describe Denisiuk holography approach and optoelectronic techniques for measuring, with sub-micrometer accuracy, shape and changes in states of deformation of MEMS structures. Examples of the holographic visualization of the MEMS switch microcantilever vibrations are presented.

2. Optical Denisiuk holography approach

The holographic interferogram of the array of microcantilevers presented in Figure 1 was recorded using Denisiuk hologram recording method [6] (He-Ne laser with the wavelength 0,6328 μm was employed).

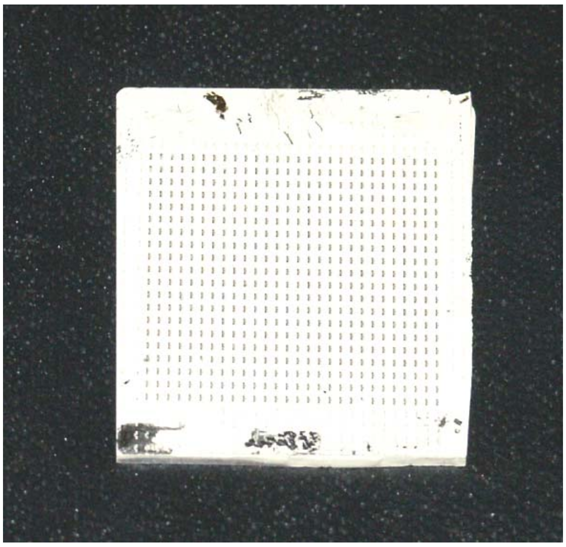


Figure 1. Array of cantilivers

The array of cantilevers was illuminated through the high density holographic material (recording density over 10000 lines per mm). The array of cantilevers was placed directly under the holographic plate and the holographic interferogram was recorded using the principles of time-average holography for vibrating opaque bodies. Denisiuk hologram recording method enables the reconstruction of holographic images in day light illumination. The optical measurement setup is illustrated in Figure2.

Fine grain silver halide holographic photo plate PFG-03C (resolving power = 10000 mm^{-1}) was used. Thus the image of stationary array of cantilevers A (Figure 1) with vibrating tips was recorded onto Denisiuk hologram. The tips of the cantilevers were brought into high frequency oscillatory motion by exposing the array plate to ultrasonic acoustic excitation. The used frequency of ultrasonic excitation was 63 kHz.

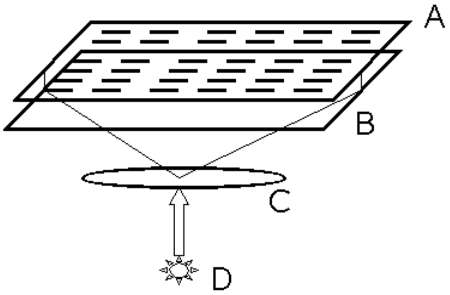


Figure 2. The schematic diagram of the holographic set-up for recording Denisiuk hologram:
A – the array of cantilevers; B – holographic plate;
C – lens; D – laser light source

After the development of the recorded hologram the holographic picture of cantilevers was reconstructed using red light diode source. Such diode source illumination is necessary to avoid the formation of speckle structure in laser image. A micro lens system was used to enlarge the image of the cantilevers (magnification up to 200 times enabling registration of the interference fringes of a single cantilever). It should be noted that the last procedure is complicated due to the fact that the quality of the magnified image is very much affected by the speckle structure of the reference laser beam. Thus the speckle microstructure of the beam was minimised using red light diode source.

Figure 3 represents time average holographic images of the harmonically excited micro cantilever beam.

Figure 3. Time average holograms of a vibrating cantilever beam

3. Digital holography methodology

Optoelectronic holography (OEH) methodologies have been successfully applied to different fields of nondestructive testing (NDT) of objects [2-10]. OEH methodologies are noninvasive, remote, and full-field-of-view capable of providing qualitative and quantitative information on shape and deformation of objects subjected to a large variety of boundary conditions and loadings. Implementation of recent technological advances in coherent light sources, computing, imaging, and detector technologies to the OEH has dramatically increased the versatility of the OEH methodologies and added the possibility of using them in microscopic setups to study MEMS structures and to investigate micromechanics of materials used for MEMS fabrication.

One OEH approach used to perform shape measurement investigations of objects consists of acquiring and processing two sets, $I(x,y)$ and $I'(x,y)$, of phase-stepped intensity patterns, recorded before and after, respectively, event effects of which are to be measured [9]. The first set of phase-stepped intensity patterns is described by

$$I_n(x,y) = I_B(x,y) + \\ + I_M(x,y)\cos[\Delta\Phi(x,y) + \theta_n] \quad (1)$$

where

$$I_B(x,y) = I_0(x,y) + I_r(x,y) \quad (2)$$

is the background irradiance, and

$$I_M(x,y) = 2\sqrt{I_0(x,y) \cdot I_r(x,y)} \quad (3)$$

is the modulation irradiance. In Eqs (1) to (3) $I_0(x,y)$ and $I_r(x,y)$ are the object and reference beams irradiances, respectively, $\Delta\Phi(x,y) = \Phi_0(x,y) - \Phi_r(x,y)$, with $\Phi_0(x,y)$ representing a random phase due to light scattering from the object of interest and $\Phi_r(x,y)$ representing a uniform phase θ_n from a smooth reference beam wavefront, θ_n is the applied n-th phase step, value of which is obtained during calibration procedures applied according to the specific phase stepping algorithm that is implemented, and (x,y) represents Cartesian coordinates of the image space.

The second set of phase-stepped intensity patterns is described by

$$I'_n(x,y) = I_B(x,y) + \\ + I_M(x,y)\cos[\Delta\Phi(x,y) + \Delta\gamma(x,y) + \theta_n] \quad (4)$$

In Eq. (4), $\Delta\gamma(x,y)$ is the change in the optical phase that occurred between acquisition of the two sets of phase-stepped intensity patterns, value of which relates to the shape or changes in state of deformation of objects of interest. With the OEH, the two sets of phase-stepped intensity patterns are processed in the display and data modes.

In the display mode, secondary interference patterns, $Q_D(x,y)$, are generated, displayed at video rates, and are modulated by a cosinusoidal function of the form

$$Q_D(x,y) = 4I_M(x,y)\cos[\Delta\gamma(x,y)/2] = \\ = \{[I_1(x,y) - I_3(x,y) + I'_1(x,y) - I'_3(x,y)]^2 + \\ + [I_2(x,y) - I_4(x,y) + I'_2(x,y) - I'_4(x,y)]^2\}^{1/2} \quad (5)$$

which represents an 8-bit resolution video image obtained after application of four phase steps: $\theta_n = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$. The display mode is used for adjusting, in real-time, the experimental parameters for accurate OEH investigations.

Such parameters include:

- beam ratio $r = \frac{avg[I_r(x,y)]}{avg[I_0(x,y)]}$ which is important to characterize and set in order to obtain an appropriate fringe visibility and also to avoid optical saturation of the CCD array detector of the CCD camera,
- phase step θ_n which is obtained by calibration and used in order to acquire accurate phase-stepped intensity patterns $I_n(x,y)$ based on which further processing is conducted. The data mode is used for quantitative investigations, which involve the determination $\Delta\gamma(x, y)$ related to the shape and/or deformation, of samples of interest [9]. The discontinuous distribution $\Delta\gamma(x,y)$, modulo 2π, is determined using double-float point arithmetic as

$$\Delta\gamma(u,v) = arctg\left(\frac{2(l_2 - l_4)}{2l_3 - l_1 - l_5}\right) \quad (6)$$

where (x,y) arguments have been omitted for clarity. Equation (6) corresponds to the implementation of the 5-phase-steps algorithm with $\theta_n = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}, 2\pi$. Application of such algorithm minimizes errors in determination of $\Delta\gamma(u,v)$ due to possible phase stepping miscalibration. Recovery of continuous spatial phase distributions $\Delta\gamma(u,v)$ requires the application of efficient phase unwrapping algorithms [7].

The principle scheme of vibration process visualization is presented in Figure 4. Magnification of the object hologram was done using microscopic optical system.

Reconstructed images of the vibration cantilivers enabled to describe the nature of those vibrations. The general view of the holographic interferograms of the microcantilivers is presented in Figure 5.

4. Conclusions

In conclusion, optical holography and digital holography methods for visualization of the modes of vibration of micromechanical systems were proposed. Both of them are used for the characterization of full field vibrations of the objects at the microscale.

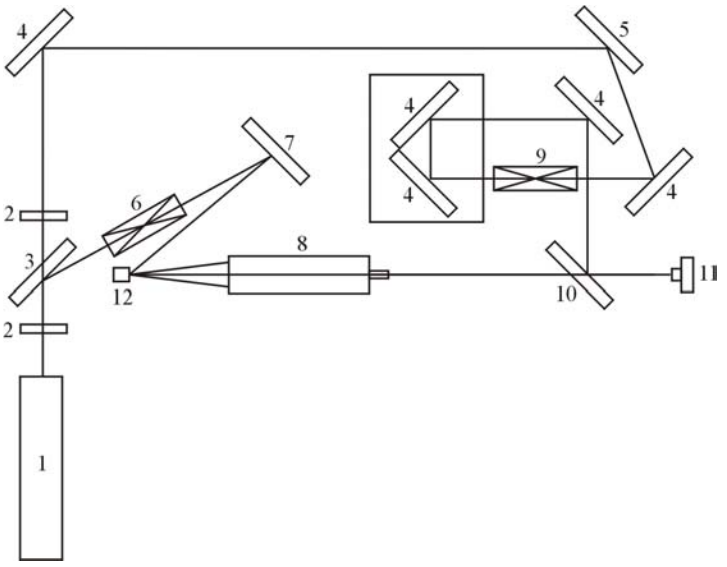
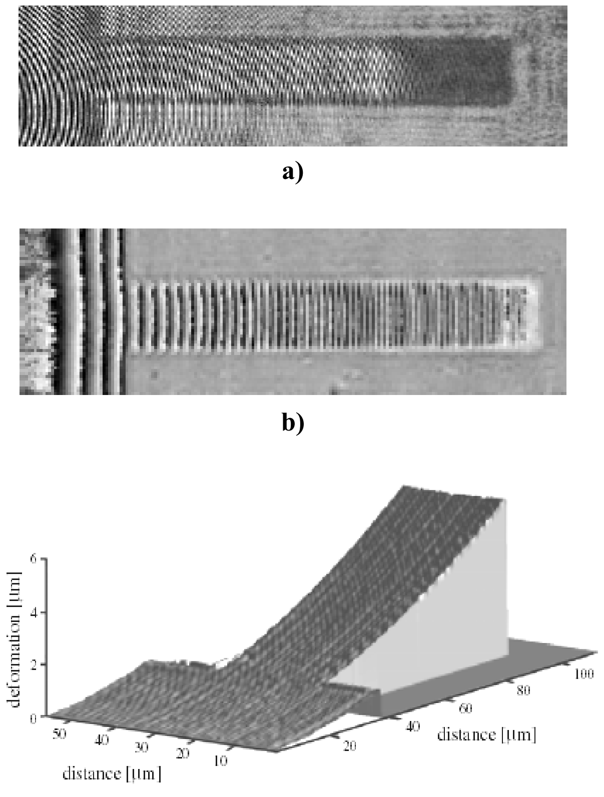


Figure 4. Schematic diagram of the microscopic holography system:
1- He-Ne laser; 2 – λ/2 plate(length of the laser wavelength); 3, 5 proximal beam splitters (PBS);
4, 7 – mirrors; 6 – spatial filter; 8 – microscope; 9 – telescope; 10 – beam splitter; 11 – CCD camera; 12 – analyzed object



a)

b)

c)

Figure 5. Holographic interferogram of the microcantiliver.
a - A hologram of the microcantilever beams;
b - a phase map image, wrapped mod 2π, of the microcantiliver beam reconstructed at distance d = 100 mm;
c – an unwrapped phase with out-of-plane deformation and dimensions expressed in microns.

With the incorporation of a local distance microscope, it well fulfills the requirements of imaging microstructures with high resolution at sufficient working distances for good illumination.

Besides performing the function of three-dimensional imaging of microstructures, the system will be especially useful in quantitative displacement or shape measurement for characterization of MEMS.

With OEHM it is possible to achieve high measurement resolutions for characterization of both shape and deformation of MEMS devices.

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