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Compact handheld digital holographic microscopy system development

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ABSTRACT

Development of a commercial prototype of reflection handheld digital holographic microscope system is presented in this paper. The concept is based on lensless magnification using diverging wave geometry and the miniaturized optical design which provides a compact packaged system. The optical geometry design provides the same curvature of object and reference waves and thus phase aberration is automatically compensated. The basic methodology of the system is developed and it further explored for 3D imaging, static deflection and vibration measurements applications. Based on the developed methodology an user-friendly software is developed suitable for industrial shop floor environment. The applications of the system are presented for 3D imaging, static deflection measurement and vibration analysis of MEMS samples. The developed system is well suitable for the testing of MEMS and Microsystems samples, with full-field and real-time features, for static and dynamic inspection and characterization and to monitor micro-fabrication process.

Keywords: Compact optical system, lensless magnification, handheld system, MEMS measurement

1. INTRODUCTION

Development of optical tools for on-line inspection and characterization of micro-devices e.g. MEMS and microelectronics systems are highly demanding and a challenging task. With the recent on-going development in technologies results as the miniaturized final device and it creates the new challenges for the existing measurement and characterization tools. The main requirements behind development of such tools are to provide feedbacks about device behaviour, controlled fabrication process, system parameters, and material properties for designing and simulation process to ensure the performance of device repeatability and reliability. The major requirement from the new characterization tools are: better imaging and highly accurate measurement performance for full 3D, larger field of view and high imaging resolution as well as to provide experimental data for computer aided engineering for real time analysis. Additionally the characterization tool should have the possibility to integrate with the device fabrication tools and machines. Existing microscopes have limitations of short working distance, limited depth of field, and limited information recording capabilities. Furthermore image acquisition and processing of the data for static and dynamic deformation measurement are added challenges that have to be incorporated into the same system. Conventional metrological methods are unable to meet these requirements. Thus the suitable approach has to be developed for this growing industry to ensure reliability and quality of the products and processes.

Digital holography (DH) technology has been developing since the last decade as a novel way for handling of light [1]. The capability of DH to store whole field three-dimensional (3D) information of the object, in digital form, in a two-dimensional (2D) hologram and to numerically focus it in any arbitrary plane offer new possibilities to address the challenges of optical metrology requirements. The significant advantages come from the numerical reconstruction of the

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object wavefront, that provides the quantitative and independent amplitude and phase information about the object. The numerical phase information can be directly converted into the object height/depth variation and provides measurement with nm accuracy [2]. DH based optical microscopy system shows great promises for Microsystems and MEMS characterization applications [3-5]. Although the potential applications of DH based microscopy system shows promising application for micro-device characterization but their stand alone bulky optical systems need the samples to be brought to the measurement stage [6]. In this paper the development of a simple, compact yet powerful DH based lensless microscopy system is presented for MEMS, Microsystems and micro-fabrication process inspection and characterization. The novelty of the system is the incorporation of lensless magnification with DH to provide a compact system suitable precisely to fulfill the micro device measurement requirements. The compact lensless design and the user-friendly and interactive software is developed for real time analysis. The developed system can be incorporated with machines to monitor process parameters or can be used for final device characterization both in static and dynamic modes. Following are the main market/industries for commercialization of the proposed system:

- MEMS: MEMS device inspection and characterization (static and dynamic), micro-Interferometry measurements, nanometer range deformation measurement capability, and 3D surface profile study.
- Micro-electronics: Thermal and stress deformation analysis on wafers, Deformation measurements in the devices due to thermal heat generation and 3D surface profiling.
- Micro-fabrication: To monitor quantitatively the fabrication process in-situ which provide the feedback for optimization of parameters.

In section 2, the development of optical design, packaging and theory of the system is presented; section 3 provides the information about the software development followed by the section 4 on some applications of the developed system and software.

2. OPTICAL SYSTEM AND METHODOLOGY DEVELOPMENT

2.1 Optical system configuration and packaging

The schematic of patent pending lensless digital holographic reflection microscope is shown in Figure 1 [7].

Figure 1 Schematic of the lensless digital holographic microscope

A point source provides a diverging beam of which is centered about the optical axis. The divergence of the beam provides the lensless magnification in the system. A beam splitter is used to separate the diverging beam; reflecting a portion towards the test object and transmitting a portion to a mirror located behind the beam splitter. The scattered light from the test object is called the object beam and the reflection beam from the mirror is the reference beam. The beam splitter transmits the object beam towards, and reflects the reference beam to a CCD sensor. The interference pattern between the object and the reference beam is converted to a digital signal by the CCD, called digital hologram, is then numerically processed to determine the desired characteristics of the object. The interference angle can be controlled by the tilting of the reference mirror, and this provides to use the system in both in-line and off-axis mode. Off-axis geometry is particularly useful for phase reconstruction from the single hologram. This system presents lensless reflection microscopy geometry by using a very simple and compact optical set-up best suited for the study of micro-size samples. The novelty of the system is the compact optical geometry with minimum number of optical components and suitable to develop as handheld system. The other advantage of the system is because of same wavefront of object and reference beams and it does not provide any spherical phase aberrations during the reconstruction of the hologram.

The presented system is most suitable for the study of highly specular objects and provides the 3D measurement from the direct phase calculation by reconstructing the single off-axis hologram. The ratio of the distances from point source to CCD and from point source to sample defines the geometrical magnification of the system. Since the distance from point source to object is constrained by the beam splitter, so it restricts the magnification of the system. The system is not perfectly suitable for the analysis of the diffused surface samples, because the object beam is scattered from the sample surface and its amplitude is significantly smaller than the reference beam amplitude and thus does not provide good contrast of the interference pattern when recorded by the CCD.

This optical system design is housed in a compact casing as shown in Figure 2. The illumination source is a single mode fiber end which provides the diverging laser beam attached to the casing. The other end of the fiber is attached to the laser. The wavelength of the light chooses according to the application and/or the required lateral resolution. For the presented system, a fiber coupled laser diode with wavelength $642nm$ is used. The diverging beam is delivered from the end of an optical fiber, where the smaller the diameter of the fiber (for example in the order of wavelength) the greater the cone of the emitted light coming through it. Therefore a smaller diameter fiber may increase the Numerical Aperture (NA) of the system and thus the system resolution.

Figure 2 Packaged handheld digital holographic microscopy system

2.2 Theory: Digital recording and numerical reconstruction of hologram

During the interference of object and reference the waves propagate along the same optical axis. Consider (x, y) be the hologram plane and the object and reference waves denoted by the $O(n_x, n_y)$ and $R(n_x, n_y)$ at the CCD plane. Here $n_x = 0, 1, \dots, N_x - 1$ and $n_y = 0, 1, \dots, N_y - 1$ are the pixel indices of the camera, and $N_x \times N_y$ is the size of the CCD sensor in pixels. The hologram is the interference of the object wave reference waves and can be written as,

$$\begin{aligned} h(n_x, n_y) &= |O(n_x, n_y) + R(n_x, n_y)|^2 \\ &= |O(n_x, n_y)|^2 + |R(n_x, n_y)|^2 + O^*(n_x, n_y)R(n_x, n_y) + O(n_x, n_y)R^*(n_x, n_y) \end{aligned} \quad (1)$$

Here O^* and R^* are the complex conjugate of O and R , respectively. The CCD, placed at the hologram plane, records the interference pattern as given in eqn. 1. For digital recording, the sampling theorem requires that the interference fringe spacing must be larger than the size of two pixels of CCD. The recorded pattern is converted into a two-dimensional array of discrete signals by using the sampling theorem. Let pixel size of the CCD is Δ_x and Δ_y , then the digitally sampled holograms, can be written as,

$$H(n_x, n_y) = [h(n_x, n_y) \otimes \text{rect}(\frac{x}{\alpha\Delta_x}, \frac{y}{\beta\Delta_y})] \times \text{rect}(\frac{x}{N_x\Delta_x}, \frac{y}{N_y\Delta_y}) \text{comb}(\frac{x}{\Delta_x}, \frac{y}{\Delta_y}) \quad (2)$$

Where $\otimes$ represents the two-dimensional convolution and $(\alpha, \beta) \in [0, 1]$ are the fill factors of the CCD pixels.

Numerical reconstruction of hologram is performed using the Fresnel diffraction theory. The hologram $H(n_x, n_y)$ is multiplied by the numerical reconstruction wave $R(n_x, n_y)$ and the numerically reconstructed wavefield $U(n_x', n_y')$ at the image plane (x', y') at distance d' from the hologram plane is obtained by using the convolution method as,

$$U(n_x', n_y') = [H(n_x, n_y)R(n_x, n_y)] \otimes [g(n_x, n_y)] \quad (3)$$

Here $g(n_x, n_y)$ is the impulse response of the system and its Fourier transform, called transfer function, is used for reconstruction and defined as [8],

$$G(n_x, n_y) = \mathfrak{F}\{g(n_x, n_y)\} = \exp\left\{\frac{2\pi i d'}{\lambda} \sqrt{1 - \frac{\lambda^2 (n_x + N_x^2 \Delta_x^2 / 2d' \lambda)^2}{N_x^2 \Delta_x^2} - \frac{\lambda^2 (n_y + N_y^2 \Delta_y^2 / 2d' \lambda)^2}{N_y^2 \Delta_y^2}}\right\} \quad (4)$$

The reconstructed wavefield can be calculated by using the convolution theorem,

$$U(n_x', n_y') = \mathfrak{F}^{-1}[\mathfrak{F}\{H(n_x, n_y)R(n_x, n_y)\} \times G\{n_x, n_y\}] \quad (5)$$

The pixel size of the reconstructed image Δ_x' and Δ_y' using this method is same as the pixel size of CCD i.e. $\Delta_x' = \Delta_x$ and $\Delta_y' = \Delta_y$. The image intensity I and phase ϕ at the real image plane can be calculated as,

$$I = |U(n_x, n_y)|^2 \text{ and } \phi = \arctan[\text{Im}(U(n_x, n_y)) / \text{Re}(U(n_x, n_y))] \quad (6)$$

2.2 Measurements methodology: 3D, static and dynamic measurement

3D height/depth measurement:

The numerically reconstructed phase information can be used for the 3D measurement i.e. height/depth measurements of the sample. If r is the refractive index of the sample (in case of transmitted coating on sample surface), then the sample height/depth t can be written as:

$$t = \frac{\lambda \phi}{4r\pi} \quad (7)$$

Static deformation measurement:

Static measurement is performed using interferometry method. In it phase information of the holograms are recorded corresponding to the two deformation states of the sample and their reconstructed phase subtraction provides the deformation characteristics. The instantaneous fast dynamic deformation of sample can also be measured using high speed CCD camera with the system. When sample surface is illuminated by the beam, the light wave reflected from the object surface can be written at the hologram plane as,

$$O(n_x, n_y) = O_0(n_x, n_y) e^{i\phi_0(n_x, n_y)} \quad (8)$$

where $O_0(n_x, n_y)$ is the amplitude of the reflected light and $\phi_0(n_x, n_y)$ is the phase that represents the object surface properties. This object wave interferes with the reference wave and hologram is recorded using CCD. On numerical reconstruction, the reconstructed real image wave can be written as:

$$U(n_x, n_y) = O_0(n_x, n_y) e^{i\phi(n_x, n_y)} \quad (9)$$

The numerical phase subtraction of the reference state from the deformed state represents the modulo 2π interference phase, which provides the deformation map. Let ϕ_0 is the phase corresponding to the static state of the object (reference state) and ϕ_1 be the phase corresponding to the deformation state, then the subtraction of the phases provides the interference pattern written as,

$$\Delta\phi_{2\pi} = \phi_1 - \phi_0 \quad (10)$$

Vibration measurement:

For a sinusoidally vibrating object, the instantaneous object wave at any instant coming from the vibrating object defined as,

$$O'(n_x, n_y, t) = O_0(n_x, n_y) e^{i\phi_0(n_x, n_y)} e^{i[\vec{K} \cdot \vec{z}_v(n_x, n_y, t)]} \quad (11)$$

where $\phi_0(n_x, n_y)$ is the phase representing the mean deformation state of the vibrating object, $\vec{K}$ is the sensitivity vector and $\vec{z}_v(n_x, n_y, t)$ is the amplitude of vibration.

Time-averaged method is used to record the hologram [9]. For this method, the frame capture time τ of the CCD should be larger than the period of object vibration. The time averaged object wave is written as,

$$O(n_x, n_y) = \frac{1}{\tau} \int_0^\tau O'(n_x, n_y, t) d\tau = O_0(n_x, n_y) \exp\{i\phi(n_x, n_y)\} \times J_0\{\vec{K} \cdot \vec{z}_v(n_x, n_y)\} \quad (12)$$

Where J_0 is the zero order Bessel function and $\phi(x, y)$ represents the phase of the object wave which contains the information both about mean static deformation and zeros of Bessel function and defined as,

$$\phi(n_x, n_y) = \phi_o(n_x, n_y) + \phi_J(n_x, n_y) \quad (13)$$

Here $\phi_o(n_x, n_y)$ contains object surface information and $\phi_J(n_x, n_y)$ is the time averaged phase. On numerical reconstruction the reconstructed real image wave is written as,

$$U(n_{x'}, n_{y'}) = O_0(n_{x'}, n_{y'}) e^{i\phi(n_{x'}, n_{y'})} J_0[\vec{K} \cdot \vec{z}_v(n_{x'}, n_{y'})] \quad (14)$$

The amplitude and phase of the numerically reconstructed real image wave is written as follows,

$$A(n_{x'}, n_{y'}) = |U(n_{x'}, n_{y'})| = O_0(n_{x'}, n_{y'}) J_0\{\vec{K} \cdot \vec{z}_v(n_{x'}, n_{y'})\} \quad (15)$$

and

$$\phi(n_{x'}, n_{y'}) = \arctan \frac{\text{Im}(U(n_{x'}, n_{y'}))}{\text{Re}(U(n_{x'}, n_{y'}))} = \phi_o(n_{x'}, n_{y'}) + \phi_J(n_{x'}, n_{y'}) \quad (16)$$

As mentioned in eqn. 15, the numerically reconstructed amplitude is modulated by the zero-order Bessel function which provides the information on the mode shape and amplitude of vibrations of the object. The numerically reconstructed phase from time-average holograms (eqn. 16) is a combination of phase due to mean static state information ϕ_o , and the time average phase ϕ_J . ϕ_o varies from $-\pi$ to $+\pi$, whereas ϕ_J is the binary phase (with values 0 and $\pm\pi$) that changes at the zeros of the Bessel function [10]. However, in the presence of both static deformation and vibrations, the phase of time averaged hologram represents the mixing of the mean deformation and the time-averaged fringes represented by the reconstructed phase information [5].

3. SOFTWARE DEVELOPMENT

Based on the developed methodology an user-friendly software is developed suitable for industrial shop floor environment. The code of this software is written with the language C++ under the environment of Visual Studio 6.0. The frame of this software is designed with the technology of Multiple Document Interface (MDI). The interfaces mainly include hologram window, intensity window, phase window, 3D view window and plot window. This software provides real-time performance, i.e. it can capture live hologram image, and reconstruct the intensity and phase images in real-time. In phase window, the user can analyze the reconstruction results on the wrapped or unwrapped phase, and view different displays of the phase image by changing the color map of these images. In this software, the color maps include gray, Jet and HSV. In phase image, the user can measure the length between two points on the surface of an object, and in plot image view the height variation. Also the user is able to do the tilt compensation when sample plane is not exactly parallel with CCD. In addition, the user can obviously view the 3D effect on the reconstruction.

4. APPLICATIONS: MEMS DEVICES INSPECTION AND CHARACTERIZATION

4.1 3D measurements from single hologram reconstruction:

The hologram of a circular MEMS diaphragm, recorded using the optical system of figure 1, is shown in figure 3 (a). The numerical reconstruction of the hologram was performed using the formula defined in eqn. 5. The reconstructed amplitude contrast and phase contrast images of the diaphragm is given in figures 3(b) and (c) respectively. Here, only the outline of the diaphragm is seen in the amplitude contrast images due to the diffraction from the edges. However the phase contrast image is significantly different from the amplitude contrast image and shows the circular fringes representing the surface profile of the diaphragm. In order to measure the height variation this wrapped phase image need to be unwrapped and the resultant phase can be converted to the height/depth variation using eqn. 7.

Figure 3 (a) Hologram of a MEMS diaphragm, (b) amplitude image, and (c) phase image

The wrapped phase can be seen clearly in figure 3(c) because of the phase jumps of more than 2π . Figure 4(a) shows the unwrapped phase image, and the quantitative value of the phase was converted to a length scale. It can also be directly used for 3D profile measurement of the sample surface. The 3D plot of the MEMS diaphragm is shown in figure 4(b). In order to calculate the height of the diaphragm surface, the line profile is plotted across the centre of the unwrapped phase contrast image and is shown in figure 4(c). It is important to note that the amplitude, phase and 3D profile of the sample is obtained from the single hologram. The developed software provides the real time reconstruction. Thus, this system is useful for the full field 3D measurement of MEMS sample surfaces in real time, no other current technology provides such measurement. The height/depth resolution of the system, obtained from the phase information is around $10nm$.

In contrast to the presented method, the similar profile can also be obtained from the other 3D measurement technologies e.g. confocal microscopy [11], phase shifting interferometry [12], and scanning probe microscopy (SPM) [13], but these techniques require the scanning process and/or recording few images before generating the 3D profile of the sample and thus cannot be used for real time measurement applications.

4.2 Static deflection measurement using interferometry:

Aluminium nitride (AlN) films have piezoelectric properties, and represent an alternative to PZT films. Out-of-plane static deflection analysis of the AlN cantilevers ($900\mu\text{m} \times 50\mu\text{m}$) was performed using the presented system [14]. The experimental set-up shown in figure 1 is used for deformation study of the cantilevers. The upper and lower electrodes were connected to the power supply and holograms were recorded corresponding to the different applied voltages between the electrodes. The phase information is reconstructed of the recorded hologram recorded at different voltages. The subtraction of the phases, as defined in eqn. 10, of the deformed state (corresponding to the applied voltage) and reference state (without applying voltage) provides the deformation fringes. Figures 5(a) & (c) show the deformation fringes for the two different voltages. Deformation fringes can be seen and different number of fringes can be clearly observed. The deformation profile along the length of middle cantilever is plotted in figure 5 (b & (d) respectively. This kind of analysis is useful to study of different parts of same device simultaneously corresponding for the same input conditions.

4.2 Vibration analysis using time-averaged method:

Time averaged holograms were recorded of a MEMS diaphragm (size 1 mm) corresponding to its one resonant frequency (103 kHz). The mode shapes of the vibrating MEMS diaphragm was obtained from the reconstruction of time-averaged holograms as shown in figure 6. The amplitude of the reconstructed amplitude image, as shown in figure 6(a), is modulated by the J_0 function (eqn. 15) and gives the vibration mode pattern. The reconstruction phase is shown in figure 6(b). For pure sinusoidal vibration of the sample, the phase provides only the time average phase can be used for better visualization of mode shape because of the binary jumps of time-average phase at zeros of J_0 function and provides same contrast for all J_0 orders. In the phase image some additional conventional interference fringes also observed that are showing the presence of mean static deformation information about the mean position during the vibrations. For the time-averaged holography the mean static fringes mix with the time-averaged fringes as given in eqn. 16.

Figure 6 Vibration analysis using time-averaged method (a) Amplitude image shows the vibration mode shape, (b) Phase image shows the time-averaged phase mixed with mean deformation phase

5. CONCLUSIONS

In this paper development of a commercial prototype handheld digital holographic microscope is presented. The lensless microscopy configuration provides the miniaturized optical design and thus a highly compact packaged system. The basic methodology of the system and its further application for 3D imaging, static deflection and vibration measurements is provided. The software for the system is developed based on the presented methodology. The diversified applications of the system are presented for MEMS applications: first the results on 3D imaging and measurement of a MEMS diaphragm are shown using a single hologram; then, the out-of-plane static deflection in cantilevers is presented for different applied voltages; and finally, the vibrations analysis of a MEMS diaphragm are presented using the time-averaged method. The developed system design and algorithm will be suitable for full-field and real-time testing and measurement of MEMS and Microsystems samples for static and dynamic inspection and characterization and to monitor micro-fabrication process in real time. The developed system can be incorporated with the device fabrication tools to monitor the process parameters and also used for final device characterization.

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