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Dynamic characterization of MEMS diaphragm using time averaged in-line digital holography

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ABSTRACT

In this paper dynamic characterization of a MEMS diaphragm is investigated using lensless time-averaged in-line digital holography. The analysis and capability of the numerically reconstructed amplitude and phase information from in-line time averaged holograms as applied to MEMS vibration are presented. Particularly the effect of mean static state on the phase in time averaged digital holography is explored. A novel double exposure method is also demonstrated using a diverging object wave suitable for dynamic characterization of small size objects. A phase jump in the static deformation fringes in the vibrating regions is observed and described and can be used for precise analysis of vibration mode shape under simultaneous presence of mean static deformation. A simple and robust tool for dynamic optical metrology of MEMS devices and micro-objects using time averaged in-line digital holography is thus proposed.

Keywords: In-line digital holography, vibration, time-averaged method, MEMS, mean static deformation

1. Introduction

Integration of mechanical elements, electronics, sensors and actuators on a common silicon substrate by micromachining technology constitute microelectromechanical systems (MEMS) which have a wide range of applications. Dynamic characterization of MEMS structures is an exigent task. Optical interferometry has been extensively used for MEMS measurements [1]. More recently, digital holography offers new possibilities in the non-invasive measurement of MEMS devices [2,3]. In digital holography, the numerical separation of amplitude and phase enables direct determination of modulo 2π interferometric phase without the need for any phase shifting method while at the same time the numerical amplitude reconstruction allows for lens-less imaging. Incorporation of microscopy with digital holographic interferometry improves the capability of measurements for Microsystems and has been explored for static measurements [4]. Dynamic Digital Holography has also attracted great interest in recent years. There are two approaches to this – the first is to use a pulse laser or high speed camera to record multiple frames which are then processed much like the static case [5, 6]. Methods such as pulse or stroboscopic digital holography require precise synchronization of the light source, specimen and the recording device, which makes the system complex. The second and more interesting approach is to use the time average method which does not require any high speed camera or a pulsed laser [7]. Most of the current dynamic digital holographic measurements have dealt with relatively large size objects (30mm and more) [8, 9]. In this paper, a lens-less in-line time average digital holography is used for dynamic measurements on relatively small object (~ 5 mm in diameter). Three main aspects of the current study are presented, which differs from reported dynamic digital

holographic systems. First, unlike most existing digital dynamic holographic systems that use off-axis geometry, this one uses an in-line lens-less geometry. The in-line digital holographic system has shown better performance due to its higher space-bandwidth product which provides a larger field of view and higher imaging resolution than the off-axis set-up [10]. Secondly, unlike existing time average digital holographic system, this method uses a double exposure time average approach to separate both the time average vibration fringes and mean deformation fringes [11]. This approach also helps suppress the background noise caused by overlapping zero-order and twin image in the in-line set-up. The third difference is that existing systems use microscope objectives to magnify the objects whereas in the proposed lens-less set-up, geometrical magnification is achieved by using a diverging object wave [13]. This enables investigation of objects of smaller size with high contrast time average fringes as well as mean deformation patterns along with full effective utilization of CCD. Furthermore, it is shown that the reconstructed phase of double exposed time averaged holograms has two parts - the first part contains information on object speckles and provides the modulo 2π mean deformation fringes, while the second part is the binary time averaged phase that is used to clearly identify the time average fringes. In the presence of changing mean deformation, the phase of time average holograms represents the mixing of both these informations. This mixing of the phase can be used to precisely study the vibration behavior of objects. A jump in the mean deformation phase is observed across the time-averaged phase which possibly represents the imbalance of the object.

2. Time averaged in-line digital holography

2.1 Recording of time average holograms

For a sinusoidally vibrating object in the (x, y) plane, the scattered object wave at any instant can be written as,

$$O'(x, y, t) = O_0(x, y) \exp[i\{\vec{K} \cdot \vec{z}(x, y)\}] \quad (1)$$

Here $O_0(x, y)$ is the amplitude of the scattered wave, $\vec{K}$ is the sensitivity vector and $\vec{z}(x, y)$ is the out-of-plane displacement which can be divided into two part: the mean deformation component ($z_o(x, y)$) and the time varying component ($z_v(x, y)$) displacements and can be written as,

$$\vec{z}(x, y) = z_o(x, y) + z_v(x, y) \sin \omega t \quad (2)$$

where ω is the frequency of vibration.

For time averaged recording, the frame capture time τ of the recording device should be larger than the period of object vibration. The time averaged object wave is thus:

$$O(x, y) = \frac{1}{\tau} \int_0^\tau O'(x, y, t) d\tau \quad (3)$$

$$O(x, y) = O_0(x, y) \exp\{i\phi(x, y)\} \times J_0\{\vec{K} \cdot \vec{z}_v(x, y)\} \quad (4)$$

Where J_0 is the zero order Bessel function and $\phi(x, y)$ represents the phase of the object wave and contains the information both about mean static deformation and zeros of Bessel function as defined in eqn. (2),

$$\phi(x, y) = \phi_o(x, y) + \phi_j(x, y) \quad (5)$$

where $\phi_o(x, y)$ contains object surface information and can be considered as source of speckle noise for pure time average case, and $\phi_j(x, y)$ is the time averaged phase [9].

The in-line time average hologram is the interference of time varying object wave with the in-line reference wave R at the CCD plane (ξ, η) , i.e.

$$H(\xi, \eta) = |O(\xi, \eta) + R(\xi, \eta)|^2 \quad (6)$$

If the CCD contains $M \times N$ pixels with pixel size $\Delta\xi \times \Delta\eta$, then the digitally sampled hologram can be written as [13],

$$H(m, n) = [H(\xi, \eta) \otimes \text{rect}(\frac{\xi}{\alpha\Delta\xi}, \frac{\eta}{\beta\Delta\eta})] \times \text{rect}(\frac{\xi}{M\Delta\xi}, \frac{\eta}{N\Delta\eta}) \text{comb}(\frac{\xi}{\Delta\xi}, \frac{\eta}{\Delta\eta}) \quad (7)$$

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

2.2 Numerical Reconstruction

The reconstruction of hologram is a diffraction process. When the same reference wave used to illuminate the hologram, the wavefield reconstructed at the distance d' at the image plane (x', y') is obtained as follows,

$$U(x', y') = \frac{e^{ikd'}}{i\lambda d'} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) \exp\left[\frac{i\pi}{\lambda d'} \{(x' - \xi)^2 + (y' - \eta)^2\}\right] d\xi d\eta \quad (8)$$

This equation can be converted into discrete form by using the parameters of the same CCD used for recording the holograms and can be written as the discrete Fresnel transformation:

$$U(k, l) = \frac{e^{ikd'}}{i\lambda d'} e^{i\pi\lambda d' \left(\frac{k^2}{M^2\Delta\xi^2} + \frac{l^2}{N^2\Delta\eta^2}\right)} \times \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} H(m, n) R(m, n) e^{\left[\frac{i\pi}{\lambda d'} (m^2\Delta\xi^2 + n^2\Delta\eta^2)\right]} e^{\left[-2\pi i \left(\frac{mk}{M} + \frac{nl}{N}\right)\right]} \quad (9)$$

where $k = 0, 1, \dots, M-1, l = 0, 1, 2, \dots, N-1$. The matrix $U(k, l)$ is thus the discrete Fourier transform of the product of hologram, $H(m, n)$, the plane reference beam $R(m, n)$ and a phase term $\exp\{(i\pi/\lambda d')(m^2\Delta\xi^2 + n^2\Delta\eta^2)\}$. The pixel size of the numerically reconstructed image varies with the reconstruction distance and is given by,

$$\Delta x' = \frac{\lambda d'}{M\Delta\xi}, \Delta y' = \frac{\lambda d'}{N\Delta\eta} \quad (10)$$

When the reconstruction distance d' equals the distance d between object and CCD during hologram recording, the real image of the object is formed at the image plane (x', y') .

The amplitude and phase of the numerically reconstructed real image wave is apart from a magnification term, as follows,

$$A(x', y') = |U(k, l)| = O_0(x', y') J_0\{\vec{K} \cdot \vec{z}_v(x', y')\} \quad (11)$$

and

$$\phi(x', y') = \arctan \frac{\text{Im}(U(k, l))}{\text{Re}(U(k, l))} = \phi_o(x', y') + \phi_I(x', y') \quad (12)$$

2.3 Double exposure method

In the in-line geometry, the zero-order and twin image waves overlap with the real image wave. In order to suppress these unwanted waves, a double exposure method is proposed. Two time average in-line holograms of the object are recorded, one corresponding to the reference state (either static or vibration), and other is the vibration state. The reconstructed wavefield for these two conditions can be written as follows,

Reference state 1

$$U_0(x', y') = O_0(x', y') e^{i\phi_0(x', y')} J_0[\vec{K} \cdot \vec{z}_0(x', y')] + U_0' \quad (13)$$

Vibration state 2

$$U_1(x', y') = O_0(x', y') e^{i\phi_1(x', y')} J_0[\vec{K} \cdot \vec{z}_1(x', y')] + U_1' \quad (14)$$

The background noise in the final reconstructed real image of the object is due to the zero-order wave and out-of-focus twin image wave and does not change with deformation states of the same object. Thus wavefield difference and the resulting intensity show the mixing of the mean static deformation fringes and the zero order Bessel fringes due to the time-average recording:

$$I = |U_0 - U_1|^2 = |O_0(x', y') [e^{i\phi_0(x', y')} J_0\{\vec{K} \cdot \vec{z}_0(x', y')\} - e^{i\phi_1(x', y')} J_0\{\vec{K} \cdot \vec{z}_1(x', y')\}]|^2 \quad (15)$$

To suppress this mixing, the amplitude and phase of the individual wavefields are extracted first and then subtracted.

2.4 Amplitude and phase analysis

As indicated in eqn (11), the numerically reconstructed amplitude of the real image wave is modulated by the zero-order Bessel function which provides the information on the mode shape and amplitudes of vibration of the object. For double exposure method the vibration information of the object is obtained by subtracting the amplitudes in states 1 and 2, similar to electronic speckle pattern interferometry (ESPI) [14].

The numerically reconstructed phase information from time average holograms (eqn. 12) is a combination of phase due to object surface roughness 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 [9]. In the reconstruction of a single time average hologram of object with rough surface, ϕ_o is the source of speckle noise, but by using the double exposure method speckle correlation fringes, representing the difference in mean static deformation in between the two exposures, are seen as modulo 2π fringes. However, in the presence of both static deformation and vibrations, the phase subtraction of time averaged hologram represents the mixing of the mean deformation and the time averaged fringes. A cluster of these phase information is presented in this paper, which facilitate the precise study of the object vibrations in the presence of mean static deformation. Obviously the behavior of mean static deformation fringes is not the same in vibrating and non-vibrating regions of the object. The presence of mean deformation is thought to create an imbalance which manifests itself in mean static deformation fringes. Thus the behavior of the mean static deformation fringes in the vibrating and non-vibrating regions of the object is useful to study the balancing situation of the object. This is explained by the phase jump of the mean deformation fringes in the vibrating regions for the MEMS diaphragm as an object.

3. Dynamic characterization of MEMS diaphragm

3.1 Experiment

The experimental set-up of time averaged in-line digital holography is shown in fig. 1. The object is an elliptical MEMS diaphragm with the major and minor axes 7 mm and

6.2 mm respectively. The diaphragm was fabricated by bonding a piezoelectric plate onto a SOI (silicon on insulator) wafer with 20 μm thick device layer. The thickness of the piezoelectric layer was thinned down to about 40 μm by using chemical/mechanical polish. The back side silicon was etched away by deep reactive ion etching. The diaphragm is excited by applying an AC driving voltage across the piezoelectric layer. The output from a frequency doubled Nd-YAG laser (532nm) is coupled into a bifurcated single mode fiber. One fiber arm is used to illuminate the object with diverging beam and the scattered beam from the vibrating object, called object beam interferes with the collimated reference beam from the second fiber. The intensity of reference beam is controlled to be similar to the object beam, by using a variable attenuator. The polarization of both the object and reference waves are maintained to get the best contrast of the interference fringes. The interference of object and reference beams are recorded on the CCD at a frame rate of 30 frames/sec. The CCD contains 2048x2024 square pixels of 9 μm in size.

The MEMS vibration frequencies are much higher than the CCD frame refreshing rate, so the recorded holograms are called the time averaged holograms. The time averaged in-line holograms are recorded for the whole range of resonant frequencies of the MEMS diaphragm and directly saved in the computer in real time. The numerical reconstruction process is performed using eqn. (9) and simulated in MATLAB.

3.2 Results

3.2.1 Vibrations mode shapes

The mode shapes of the vibrating MEMS diaphragm are obtained from the reconstruction of time-averaged in-line holograms recorded corresponding to the resonant

frequencies. The amplitude of the reconstructed real image wave, which is modulated by the J_0 function, gives the mode pattern. Fig. 2 (a)-(h) show the mode shapes corresponding to the eight resonant frequencies. The vibration modes shown in fig 2 can be identified as, (a) (0,1) at 14 kHz; (b) (1,1) at 29 kHz; (c) (2,1) at 45 kHz ; (d) (0,2) at 57 kHz, (e) (3,1) at 70 kHz; (f) (4,1) at 90 kHz, (g) (1,2) at 105 kHz, (h) (0,3) at 125 kHz. (i) (6,1) at 145 kHz, and (j) (0,4) at 175 kHz, where the number in the parentheses refers to the torsional and bending modes. These patterns can be obtained either by reconstruction of single time average hologram, or by subtraction of holograms in two states at the same frequency. The effect of zero-order term can be suppressed either by high pass filtering of the hologram before reconstruction or by using the double exposure method discussed before. The reconstructed mode pattern shows good fringe contrast, comparable to images using off-axis geometry for bigger size objects. The use of diverging beam here provides the two advantages - firstly it magnifies the object wave which helps in effective utilization of the entire CCD area, and secondly this kind of geometry is useful to reduce the effect of twin image during reconstruction which creates background noise in real image for in-line digital holography.

3.2.2 Mean deformation and time averaged phase analysis

The main advantage in using digital holography is to obtain the quantitative phase information of the reconstructed image wave. As discussed previously, the numerical reconstructed phase from time-averaged holograms contains two parts, the first part represents object surface roughness information and can be used for measurement of mean static deformation using double exposure method, while the second part is called

time average phase which shows the zeros of the J_0 function. Since the quality of time averaged fringes reconstructed by the amplitude, reduces as the fringe order increases, this limitation can be overcome with the reconstruction of time average phase. For pure sinusoidal vibration of the object, the subtraction of phases of time average and reference hologram provides only the time average phase. This is shown in Fig 3(a)-(c) corresponding to the frequencies (a) 14KHz, (b) 45KHz, and (c) 105KHz. Compared to fig 2, all zeros of the J_0 function can be clearly identified from the time average phase.

Although the time average phase contains binary values (with numerical values 0 & $\pm\pi$), it provides a clear representation of the zeros of J_0 function; while the simultaneous presence of static phase appears as the speckle noise. The double exposure method cannot completely remove this noise because of the stochastic variations of speckles in the two exposures. This effect can be seen in Fig. 3. In order to explore the mixing of the phase information during phase subtraction, first we have considered the case of pure static deformation which is achieved by selecting a non-resonant frequency and applying an off-set voltage to the membrane between exposures. The phase subtraction represents modulo 2π interference phase same as in conventional digital holographic interferometry. Fig. 4 shows the pure mean static deformation fringes obtained from time averaged in-line holograms. The holograms are recorded for a non resonant frequency 25 KHz, at different voltage with increasing offset voltage applied by the frequency generator as in figs. 4 (a) to (c).

Mixing of the phase fringes is best visualized when the applied offset voltage excites the membrane in resonance. The mixing shows the cluster of mean deformation and time average phases, which represents the exact vibration behavior of the membrane in the

presence of mean static deformations. Figure 5(a)-(c) show the patterns corresponding to the different mean and vibration amplitudes at a resonant frequency of 15 KHz. For double exposure recording, the reference hologram is recorded without vibration, and the time-averaged holograms recorded with driving voltages of 1.0, 1.5, and 2.0 volts and corresponding offset voltages 0.75, 1.5, and 2.5 volts respectively. It can be clearly seen in Fig 5(a) that the mean deformation fringe also appears inside the time average phase with a phase jump. This phase jump may be attributed to the balancing condition of the membrane created by the offset voltage. As the offset voltage increases, the number of fringes inside the time average fringe also increases (fig 5(b) and (c)).

4. Conclusion

The time averaged in-line digital holographic interferometry has been successfully implemented for dynamic characterization of MEMS diaphragm. The reconstructed wave of the time averaged hologram provides the information on the vibration mode as well as the mean static deformation of the sample under test. A double exposure method is also presented by using the phase information for dynamic characterization of MEMS diaphragms. It is proved that the subtraction of phase information of the holograms recorded at the vibration state and reference state shows that a cluster of the time average and mean deformation fringes which can be used to analyze the balancing condition of the vibrating membrane. The interference fringes are also obtained in time average phase with a phase jump compared to the main deformation fringes. Thus the proposed method of time averaged in-line digital holography is a robust and potential tool for dynamic optical metrology of MEMS.

References:

1. E. Novak, MEMS metrology technique, Proc. SPIE. 5716 (2005) 173-181.
2. G. Coppola, P. Ferraro, M. Iodice, S.D. Nicola, A. Finizio, and S. Grilli, Meas. Sci. Technol. 15 (2004) 529-539.
3. L. Xu, X. Peng, J. Miao, and A.K. Asundi, Appl. Opt. 40 (2001) 5046-5051.
4. L. Xu, X. Peng, J. Miao, and A.K. Asundi, Proc. SPIE. 4778 (2002) 11-20.
5. G. Pedrini, P. Froning, H. Fessler, and H.J. Tiziani, Opt. & Las. Technol. 29 (1997) 505-511.
6. G. Pedrini, W. Osten, and M.E. Gusev, Appl. Opt. 45 (2006) 3456-3462.
7. P. Picart, J. Leval, D. Mounier, and S. Gougeon, Opt. Lett. 28 (2003) 1900-1902.
8. N. Demoli, and D. Vukicevic, Opt. Lett. 29 (2004) 2324-2326.
9. P. Picart, J. Leval, D. Mounier, and S. Gougeon, Appl. Opt. 44 (2005) 337-343.
10. F. Zhang, J.D.R. Valera, I. Yamaguchi, M. Yokota, G. Mills, Opt. Rev. 11 (2004) 297.
11. L. Xu, X. Peng, Z. Guo, J. Miao, and A. Asundi, Opt. Express 13, (2005) 2444-2452
12. A. Asundi, and V.R. Singh, Appl. Opt. 45 (2006) 2391-2395.
13. G. Pedrini, and H.J. Tiziani, Appl. Opt. 41 (2002) 4489-4496.
14. C. Guo, L. Zhang, R. Rong, and H. Wang, Opt. Eng. 42 (2003) 2768-2771.
15. O.J. Lokberg, J. Acoust. Soc. Am. 76 (1984) 1783-1791.

Fig. 1 Experiment set-up of time-averaged in-line digital holographic interferometry

Fig 2. Vibration modes shapes corresponding to the resonant frequencies (a) 14KHz, (b) 29KHz, (c) 45KHz, (d) 70KHz, (e) 90KHz, (f) 105KHz, (g) 145KHz, and (h) 175KHz

Fig. 3 Time average phase representing the binary jumps corresponding to the zero of the
Bessel function

Fig. 4 Modulo 2π interference phase representing mean static deformation obtained by applying offset voltage at non resonant frequencies

Fig. 5 Mixing of mean deformation and time average phases, representing the balancing of the diaphragm in the presence of both vibration and mean deformation