Double exposure time averaged in-line digital holography

Singh, Vijay Raj; Anand, Asundi; Miao, Jianmin

2007

Singh, V. R., Anand, A., Miao, J. (2007). Double exposure time averaged in-line digital holography. Paper presented at the Optical Measurement Systems for Industrial Inspection v, Munich, 6616.

<https://hdl.handle.net/10356/94354>

<https://doi.org/10.1117/12.724470>

© 2007 COPYRIGHT SPIE--The International Society for Optical Engineering. Personal use of this material is permitted. Permission from SPIE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: <http://dx.doi.org/10.1117/12.724470>.

Downloaded on 26 Apr 2023 22:05:10 SGT

Double exposure time averaged in-line digital holography

Vijay Raj Singh, Anand Asundi, and Miao Jianmin

School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798

ABSTRACT

Theory, analysis and applications of digital in-line holography are presented for metrological applications. Particularly time averaged in-line digital holography is explored for dynamic characterization of membranes and MEMS diaphragms. The analysis and capability of numerically reconstructed amplitude and phase information from time averaged holograms is presented. Reconstructed amplitude provides the vibration mode shapes by showing the time average fringes that are modulated by zero-order Bessel function, same as in conventional time-averaged holography. However the numerical phase information divided in two parts, the first part represents the surface roughness information of object and is a source of noise for single exposure, and the second part called the time average phase. By using a novel double exposure method, the reconstructed phase information from time averaged holograms can be used for mean static deformation as well for better visualization of time averaged fringes. In case of the vibrating objects with simultaneous mean static deformation, the phase information mixes together and used for precise analysis of vibration behaviors. The use of double exposure method also suppress the noise from the real image wave, caused by overlapping of zero-order term and twin image wave because of in-line geometry. The experimental results are presented for vibrations of aluminum membrane with 10mm in size, and also for a MEMS diaphragm with 6mm in size.

Keywords: Time-averaged method, mean static deformation, dynamic characterization, speckled Wavefront, MEMS.

1. INTRODUCTION

In digital holography (DH), holograms are recorded in digital form using CCD sensors and then numerically reconstructed by computers [1]. Numerical reconstruction process allows the quantitative analysis of amplitude and phase of the object wavefields. It provides a wide range of DH applications such as metrology [2], micro-interferometry [3], 3-D imaging[4], and particles analysis[5]. Reconstructed wave in holography contains basically three parts: called real image wave, twin image wave and zero-order term. Generally off-axis geometry is used to separate the twin and zero-order term from real image wave, this can be achieved by giving an offset angle between object and reference waves. The commercially available CCD has limited resolution and sensing area. Thus digital sampling restricts the angle between object and reference wave for few degrees only, and also full sensing area is not utilized for numerical reconstruction process of real image wave with off-axis geometry. On the other hand, in-line geometry can be utilized to overcome these problems, along with additional advantages of higher imaging resolution and larger field of view [6]. The problems of overlapping of twin image wave and zero-order term with real image wave can be suppressed using various methods [7]. In particular, for displacement measurements, the use of double exposure method can automatically suppress the unwanted term [8].

Digital Holography has also been explored for dynamic metrology and got great interest in recent years. Basically there are two approaches to this – the first uses pulse laser or high speed camera to record multiple holograms corresponding to different dynamic states of the object and then processed like the static case [9]. The second approach uses the method so called the time averaged-method, where holograms recorded the average of different dynamic states of the object [10]. This time averaged approach is very useful for vibrational analysis object. In this paper, a lens-less in-

Further authors' information: Vijay Raj Singh: vr.singh@pmail.ntu.edu.sg, Anand Asundi: anand.asundi@pmail.ntu.edu.sg, Miao Jianmin: mjmmiao@ntu.edu.sg

line time average digital holography is presented for vibration measurements of smaller objects. Three main aspects of the current study are presented, which differs from previously reported dynamic digital holographic systems. First, the present work uses the in-line geometry. Secondly, unlike existing time average digital holographic system, this method uses a double exposure time average approach to 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 setup, geometrical magnification is achieved by using a diverging object wave. This enable investigation of objects of smaller size with high contrast time average fringes as well as mean deformation patterns alongwith full effective utilization of CCD. The reconstructed phase of time averaged holograms divided into two parts - the first part contains information on object speckles and can provides the modulo 2π mean deformation fringes by using double exposure method, while the second part is the binary time averaged phase representing the zeros of vibration fringes modulated by zero order Bessel function. In the presence of changing mean deformation during vibrations, the double exposure time average holograms represent the mixing of both the phase information.

The paper is organized as follows. In Section 2, the theory of time averaged in-line digital holography is discussed with the methodology of double exposure method. Section 3 is the experimental part. Results for vibration study of aluminum membrane and MEMS diaphragm are presented in section 4. Section 5 concludes the paper.

2. TIME AVERAGED IN-LINE DIGITAL HOLOGRAPHY

2.1 Recording of time averaged in-line digital 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: first is the mean deformation component ($z_O(x, y)$) and second the time varying component ($z_v(x, y)$) displacements. Thus $\vec{z}(x, y)$ can be written as $z_O(x, y) + z_v(x, y) \sin \omega t$, where ω is the frequency of vibration.

The hologram is the in interference of object and the in-line reference waves. For time averaged recording, the frame capture time of the CCD should be larger than the period of object vibration. The in-line time average hologram is the interference of time varying object wave O with the in-line reference wave R at the CCD plane (ξ, η) , i.e.

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

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,

$$H(m, n) = [H(\xi, \eta) \otimes \text{rect}(\frac{\xi}{\alpha\Delta\xi}, \frac{\eta}{\beta\Delta\eta})] \times \text{rect}(\frac{\xi}{M\Delta\xi}, \frac{\eta}{N\Delta\eta}) \text{comb}(\frac{\xi}{\Delta\xi}, \frac{\eta}{\Delta\eta}) \quad (3)$$

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 by the diffraction integral can be written as follows,

$$U(x', y') = \frac{e^{ikd'}}{i\lambda d'} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) \exp\left[\frac{i\pi}{\lambda d'} \{(x' - \xi)^2 + (y' - \eta)^2\}\right] d\xi d\eta \quad (4)$$

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 [1]:

$$U(k, l) = \frac{e^{ikd'}}{i\lambda d'} e^{i\pi\lambda d' \left(\frac{k^2}{M^2 \Delta \xi^2} + \frac{l^2}{N^2 \Delta \eta^2}\right)} \times \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} H(m, n) R(m, n) e^{\left[\frac{i\pi}{\lambda d'} (m^2 \Delta \xi^2 + n^2 \Delta \eta^2)\right]} e^{-2\pi i \left(\frac{mk}{M} + \frac{nl}{N}\right)} \quad (5)$$

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 $\exp\{(i\pi/\lambda d')(m^2 \Delta \xi^2 + n^2 \Delta \eta^2)\}$.

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 time averaged reconstructed object wave is given as:

$$U(x, y) = \frac{1}{\tau} \int_0^{\tau} O'(x, y, t) d\tau \quad (6)$$

$$U(x, y) = O_0(x, y) \exp\{i\phi(x, y)\} \times J_0\{\vec{K} \cdot \vec{z}_v(x, y)\} \quad (7)$$

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 and can be written as $\phi(x, y) = \phi_0(x, y) + \phi_f(x, y)$, where $\phi_0(x, y)$ contains object surface information and can be considered as source of speckle noise for pure time average case, and $\phi_f(x, y)$ is the time averaged phase.

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

$$A(x', y') = |U(k, l)| = O_0(x', y') J_0\{\vec{K} \cdot \vec{z}_v(x', y')\} \quad (8)$$

and

$$\phi(x', y') = \arctan \frac{\text{Im}(U(k, l))}{\text{Re}(U(k, l))} = \phi_o(x', y') + \phi_f(x', y') \quad (9)$$

2.3. Double exposure method

The overlapping of the zero-order and twin image waves with the real image wave degraded the image quality during reconstruction process. Double exposure method is presented to suppress these unwanted waves. In this method two time average in-line holograms are recorded of the object: one corresponding to the reference state and other of the vibration state. The numerically reconstructed wavefields corresponding to these two states can be written as follows,

Reference state

$$U_0(x', y') = O_0(x', y') \exp[i\phi_0'(x', y')] J_0[\vec{K} \cdot \vec{z}_0(x', y')] + U_0' \quad (10)$$

Vibration state

$$U_1(x', y') = O_0(x', y') \exp[i\phi_1'(x', y')] J_0[\vec{K} \cdot \vec{z}_1(x', y')] + U_1' \quad (11)$$

The subtraction of these two wavefields suppresses the background noise in the final reconstructed real image. It is because the sum of the zero-order wave and out-of-focus twin image does not change with deformation states for the same object. But since the wavefield contains amplitude as well as phase information thus the wavefields difference resulting intensity show the mixing of the mean static deformation fringes and the zero order Bessel fringes due to the time-average recording [11]. In order to suppress this mixing, the amplitude and phase of the individual wavefields are extracted first and then subtracted.

The numerically reconstructed amplitude of the real image wave represents the zero-order Bessel function, which provides the information about the mode shape and amplitudes of vibration of the object. It can be achieved by using the double exposure method, where the vibration information of the object is obtained by subtracting the amplitudes of the recorded holograms from the reference hologram.

On the other hand, the numerically reconstructed phase information of time average holograms provides the phases due to object surface roughness information ϕ_o , and other because of time average recording ϕ_j . The phase ϕ_o varies from $-\pi$ to $+\pi$ and considered as the source of speckle noise in the reconstruction of single hologram, while ϕ_j is the binary phase (with values 0 and $\pm\pi$) which changes at the zeros of the Bessel function. By using double exposure method ϕ_o provides the speckle correlation fringes that represents the difference in static deformation between the two exposures, are seen as modulo 2π fringes. But, in the simultaneous presence of time averaged vibration modes, the phase subtraction represents the mixing of the mean deformation and the time averaged fringes. The mixing of these phase fringes can provide the exact behavior of the object vibrations in the presence of mean static deformation.

3. EXPERIMENTS

The experimental set-up for in-line digital holography used for vibration study is shown in Fig. 1. A frequency doubled Nd-YAG laser operating at 532 nm is used and its output is coupled into a bifurcated single mode fiber. One fiber arm is used to illuminate the vibrating object with diverging beam, 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 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.

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

4. RESULTS FOR THE STUDY OF VIBRATIONS

4.1 Vibrations modes analysis using numerical reconstructed amplitude:

The mode shapes of the vibrating objects can be represented by displaying the numerically reconstructed amplitudes from the time averaged holograms recorded corresponding to the resonant frequencies. Since the amplitude of the reconstructed real image wave is modulated by the J_0 function gives the mode pattern, so the visualization of the higher order fringes becomes poor because of reduce of the amplitudes of higher order J_0 function. Fig. 2 shows the mode shapes of a circular aluminum membrane with size 10mm. The membrane has been fixed at the boundaries and is harmonically excited in centre using an earphone which is tuned to different resonant frequencies and amplitudes. The vibration modes corresponding to the resonant frequencies 6.2 KHz, 7.2 KHz, and 8.2 KHz are shown in fig. 2(a), (b) and (c) respectively. 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 [12].

The vibration modes of an MEMS diaphragm also studies with the same methodology and shown in fig 3. Here the vibrations of an elliptical MEMS diaphragm with the major and minor axes 7 mm and 6.2 mm respectively, are studied. 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. Fig 3(a), (b) and (c) show the vibration mode pattern at the exciting frequencies 10KHz, 45KHz and 57KHz are shown.

Fig. 2 Vibration modes of aluminum membrane of size 10mm at the resonant frequencies (a) 6.2 KHz, (b) 7.2 KHz and (c) 8.2 KHz

Fig. 3 Vibration modes of MEMS diaphragm corresponding to the frequencies (a) 10 KHz , (b) 45 KHz and (c) 57 KHz

4.2 Phase analysis

The numerical reconstruction of phase information is the main advantage of using digital holography, it is most suitable for metrological applications. In time average digital holography, as discussed before the numerical reconstructed phase from time-averaged holograms represents basically two separate information, the first part shows the roughness information of object surface and can be used for measurement of mean static deformation using double exposure method, on the other hand the second part is the time average phase which is in binary nature and changes at the zeros of the J_0 function. The visualization of the mode pattern represented by the displaying the amplitudes of the time average holograms reduce as the fringe order increases. This limitation can be overcome with the reconstruction of time average phase. In case of the pure sinusoidal vibration of the object, the subtraction of phases of time average (vibration state) and reference hologram (rest state) provides only the time average phase. It is represented in fig 4, here the subtraction of phase is shown for the MEMS diaphragm corresponding to the resonant frequencies at 10KHz and 45KHz respectively. The simultaneous presence of the means static phase with the time averaged phase creases the background noise even there is no change in the mean static state during double exposure. It is because if the stochastic change of the speckles during the double exposure, this effect can be seen in Fig 4.

If there is any change in the mean state of the membrane between the double exposures, it can also be calculated by phase subtraction. This subtraction shows the mixing of the phase information. In order to show the mixing effect, the hologram of the MEMS diaphragm is recorded, corresponding to the resonant frequency at an excitation signal with an off-set voltage between the exposures. Fig. 5 shows the phase subtracted pattern, the same resonant frequencies as presented in fig 4 are selected here. The mixing of the fringes can be seen, the diaphragm is slightly deformed at the

centre as seen by the modulo 2π mean deformation fringes, the time averaged phase fringes can also be seen with the mean deformation fringes.

Fig 4 Time averaged phase showing the vibration modes of MEMS diaphragm corresponding to the resonant frequencies (a) 10 KHz and (b) 45 KHz

Fig 5 Phase subtraction shows the combined fringe pattern (vibration modes and mean static deformation) in the presence of resonant frequencies and mean static deformation frequencies (a) 10 KHz and (b) 45 KHz

5. CONCLUSIONS

In this paper a double exposure time averaged in-line digital holography has been successfully presented for vibration analysis of smaller objects. The analysis and capability of numerically reconstructed amplitude and phase information from time averaged holograms is presented. 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 noble double exposure method is presented for vibrations study, which is most suitable for suppression of in-line zero-order term and twin image wave from real image wave, it does not require any pre-processing requirement of the holograms. The proposed method of time averaged in-line digital holography is a robust and potential tool for dynamic optical metrology of smaller objects.

REFERENCES

1. U. Schnars and W. P. O. Juptner, "Digital recording and numerical reconstruction of holograms," *Measurement Science and Technology*, vol. **13**, pp. R85-R101, 2002.

2. V. R. Singh and A. Asundi, "Advances in dynamic metrology using in-line digital holographic interferometry," in *Interferometry XIII: Applications*, E. L. Novak, W. Osten and C. Gorecki, Eds., 6293, p. 629306, SPIE, San Diego, CA, USA, 2006.
3. L. Xu, X. Peng, J. Miao and A. Asundi, "Studies on digital microscopic holography with applications to microstructure testing," *Applied Optics*, vol. **40**, pp. 5046-5051, 2001.
4. W. J. Arora, W. Sun, K. Tian, P. Stellman, L. Waller and G. Barbastathis, "Three dimensional optics for three dimensional imaging: physics, fabrication, and computation," in *Optical Micro- and Nanometrology in Microsystems Technology*, C. Gorecki, A. K. Asundi and W. Osten, Eds., 6188, p. 618810, SPIE, Strasbourg, France, 2006.
5. W. Xu, M. H. Jericho, I. A. Meinertzhagen and H. J. Kreuzer, "Digital in-line holography of microspheres," *Applied Optics*, vol. **41**, pp. 5367-5375, 2002.
6. L. Xu, X. Peng, Z. Guo, J. Miao, and A. Asundi, "Imaging analysis of digital holography," *Opt. Express*, vol. **13**, pp. 2444-2452, 2005.
7. T.M. Kreis, and Werner P.O. Juptner, "Suppression of DC term in digital holography", *Opt. Eng.*, vol. **36**, , pp. 2357-2360, 1997.
8. Lei Xu, Xiaoyuan Peng, Jianmin Miao, Anand K. Asundi, "Characterization of microstructures with in-line digital micro-holo-Interferometry", *Proc. SPIE*, Vol. **4275**, pp. 53-60, 2001.
9. G. Pedrini, PH. Froning, H. Fessler, and H.J. Tiziani, "Transient vibration measurement using multi-pulse digital holography," *Opt. & Las. Technol.* Vol. **29**, pp. 505-511, 1997.
10. P. Picart, J. Leval, D. Mounier, and S. Gougeon, "Time-averaged digital holography," *Opt. Lett.* vol. **28**, pp. 1900-1902, 2003.
11. A. Asundi and V.R. Singh, "Time-averaged in-line digital holographic interferometry for vibration analysis," *Appl. Opt.* vol. **45**, pp. 2391-2395, 2006.
12. P. Picart, J. Leval, D. Mounier, and S. Gougeon, "Some opportunities for vibration analysis with time averaging in digital Fresnel holography", *Appl. Opt.*, Vol. **44**, No. 3, pp. 337-343, 2005.