Optik 122 (2011) 49–54

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Measurement of static and vibrating microsystems using microscopic TV holography

U. Paul Kumar, N. Krishna Mohan *, M.P. Kothiyal

Applied Optics Laboratory, Department of Physics, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 12 May 2009
Accepted 26 October 2009

Keywords:
Microscopic TV holography
Microsystems
MEMS
Phase shifting
Static and vibration fringe analysis

ABSTRACT

This paper describes a microscopic TV holographic arrangement to study the static and vibrating microsystems. In the optical setup, the object beam and the reference beam arms are provided with a phase shifting mirror and a bias phase modulation mirror to carry out the measurement of the out-of-plane deformation and the vibration amplitude fields, respectively. A long working distance microscope is used in the setup for magnifying and imaging the objects on to the CCD camera. For static fringe analysis, the system is used in double exposure subtraction mode of operation, while for vibration fringe analysis, it is used in the time average contrast reversal refreshing mode of operation. An improved approach for qualitative analysis of time averaged fringes helps in reducing the number of frames required for analysis. The usefulness of the system is demonstrated by examples of static and vibration measurements for different microobjects.

1. Introduction

Static and vibration measurements are required in the field of microsystems, for the characterization of micro-electromechanical systems (MEMS) such as cantilever micro-beams, micro-bridges, or membranes [1,2]. For the characterization of motion and response time of the moveable microstructures under static and dynamic loading conditions requires a simple and robust optical measuring system [3,4]. Speckle correlation technique such as TV holography (TVH) or digital/electronic speckle pattern interferometry allows both static and dynamic measurements with high sensitivity and resolution [5,6]. Two modes of operation are commonly employed in TV holography. The speckle correlation subtraction method, applied for static deformation fringe analysis and the time average method, which is applied for studying vibrating objects [5–8]. In either case, fringe overlaid images of the object under study are obtained, where the fringes denote contours of constant surface deformation or constant vibration amplitude. The size of the objects that can be evaluated using the TV holography covers a wide range from few meters such as space craft engineering structures to few hundred micrometer such as in microsystems. For microsystems analysis, the optical arrangement uses a microscopic imaging system in the setup [6,9,10].

In this paper, we discuss a modified microscopic TV holographic system that can be used for the measurement of out-of-plane deformation and amplitudes of vibration at resonant frequencies on microsystems. In the interferometric arrangement, the object arm is provided with a phase shifting mirror for introducing phase steps whereas a PZT mirror in the reference wave provides the bias phase modulation [7,8]. A long working distance microscope is used in the setup for magnifying and imaging the microsystems on to the CCD camera [10]. For static fringe analysis, we use an error compensating four step difference-of-phases method [11]. For this, we store four phase shifted images before and after loading the micro-specimen for evaluating the out-of-plane deformation phase map. For vibration fringe analysis, we combine the contrast reversal method with the reference phase modulation technique for synchronizing both frequency and phase between the object and the reference beam excitations. This will allow to introduce bias voltage to the reference beam to shift the time average Bessel fringes similar to conventional phase shifting of cosine fringes. A four step phase shifting algorithm is used [11] for generating the wrapped phase map. The conventional median filtering with 3×3 window [12] is used to further reduce the speckle noise associated with the wrapped phase map. A multi-grid algorithm [13] is adopted for phase unwrapping. The development of the system along with experimental results on microobjects for both static and vibration measurement is presented.

2. Microscopic TV holographic (MTVH) system

The schematic of the microscopic TV holographic system for the measurement of out of plane static deformation as well as

* Corresponding author. Tel.: +91 44 22574892; fax: +91 44 22570509.
E-mail address: nkmohan@iitm.ac.in (N. Krishna Mohan).

0030-4026/$ - see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2010.02.002

vibration amplitudes of microsystems is shown in Fig. 1. The narrow beam from a 50 mW laser beam from a diode pumped solid state 532 nm CW Nd: YAG laser (Compass^{TM}315M) is divided into two beams using a beam splitter (BS_1). One beam is expanded using a spatial filtering setup (SF) and collimated with a 150 mm focal length collimating lens (CL) to act as an *object beam* to illuminate the object via a mirror M_1, a piezoelectric transducer mirror, PZTM (STr 25/150/6 PZT from Piezo-Mechanik) and a cube beam splitter (BS_2). The PZTM is driven by an amplifier, A_1 (LE150 from Piezo-Mechanik), which is interfaced to a PC with a DAQ card (NI6036E). The scattered object beam from the specimen enters the microscopic imaging system via the same cube beam splitter (BS_2). The microscopic imaging system consists of a Thales-Optem Zoom 125C long working distance microscope (LDM) with extended zoom range, and a Sony 2/3″ CCD camera (XC-ST70CE). The resolution of the CCD is 752(H) × 582(V) pixels and the size of each pixel is 11.6 μm (H) × 11.2 μm (V). The CCD is interfaced to a PC with an NI1409 frame grabber card. The Zoom LDM provides a 12.5:1 zoom ratio, at working distance of 89 mm with 1.0 × objective. The magnification of the imaging system can be varied in steps (1.0 × –12.5 ×) and the specimen dimensions of 8.4 mm × 6.3 mm at low magnification (1.0 ×) and 0.68 mm × 0.51 mm at high magnification (12.5 ×) cover the full area of the 2/3″ CCD. The divided second beam from the beam splitter (BS_1) serves as a smooth *reference beam* and illuminates the phase modulation reference mirror (PMRM, Karl Stetson Associates – PZT7K). The PZT7K allows for analyzing the vibration amplitudes of frequencies up to 7 kHz. Further the maximum allowed bias voltage to the PMRM mirror is ± 30 V for introducing the bias phase modulation. The reference beam also expanded using a spatial filtering setup (SF) and collimated with the support of a 150 mm focal length collimating lens (CL). The reference beam enters the microscopic imaging system via the same cube beam splitter (BS_2). The scattered object wave and the smooth reference wave are combined coherently onto the CCD plane. A neutral density filter (NDF) in the reference beam allows to control the intensity ratio between the object and reference wave. In the present arrangement, the collimated illumination and the observation beams are in-line and hence the sensitivity vector is perpendicular to the test object. For static fringe analysis, the PZTM is calibrated to obtain the desired phase shifted frames before and after loading the object.

For vibration analysis we have used the system in time-average refreshing reference image mode of operation. For this we have used the channel-1 (CH_1) and channel-2 (CH_2) of the external dual function generator (DFG) that consists of two National Instruments, NI PXI5402 cards for harmonic excitation of the object and the reference mirror (PMRM), respectively. The channel-1 is connected to an amplifier A_2 (Spranktronics India) to control the amplitude of the object excitation. The channel-2 allows for excitation of the PMRM mirror at the same frequencies as that of the object excitation to introduce the bias vibration. The DFG is activated through the computer and using LabVIEW. program for varying the frequency, the phase and the amplitude between the two channels (CH_1 and CH_2). In addition, the PZTM in the setup is also used for shifting the scattered object beam by 180° for introducing the contrast reversal refreshing reference time average image to subtract from the preceding time average image of the current one to remove the background DC in order to enhance the contrast of the time average fringe patterns [14,15]. Programs based on LabVIEW have been developed for storing the frames for real-time visualization and storing the phase shifted frames for static and vibration fringe analysis.

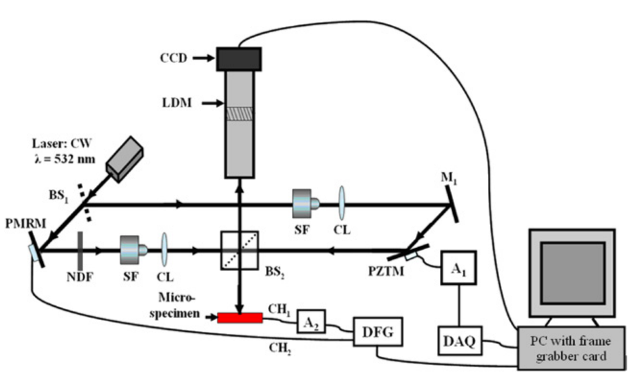

Fig. 1. Schematic of the microscopic TV holographic system for measurement of static and vibrating Microsystems: SF, spatial filter; BS_1, beam splitter; BS_2, cube beam splitter; NDF, neutral density filter; M_1, mirror; PZTM, piezoelectric transducer mirror; A_1, amplifier; DFG, dual channel function generator; PMRM, phase modulated reference mirror; A_2, amplifier for object excitation; and DAQ, digital to analog converter card.

3. Fringe analysis

3.1. Static fringe analysis

For static fringe analysis, the piezoelectric transducer mirror, PZTM in the setup (Fig. 1) is activated to store the four $\pi/2$ phase shifted images that represent the initial state of the object. The intensity of the four phase shifted frames can be expressed as [1]

$$I_{bn} = I_o(1 + V\cos(\phi + \alpha_n)) \tag{1}$$

where I_o is the bias intensity, V is the visibility, ϕ is the random speckle phase difference, and α_n is the phase step value (0, $\pi/2$, π, and $3\pi/2$), and n=1, 2, 3, 4.

The phase distribution before deformation can be obtained as [1]

$$\phi = \arctan\left(\frac{I_{b1} - 3I_{b2} + I_{b3} + I_{b4}}{I_{b1} + I_{b2} - 3I_{b3} + I_{b4}}\right) \tag{2}$$

The intensity distribution of four $\pi/2$ phase shifted images for the deformed state of the object can be expressed as [1]

$$I_{an} = I_o(1 + V\cos(\phi + \Phi + \alpha_n)) \tag{3}$$

where I_{an} are the phase shifted frames after deformation and Φ is the fringe locus function due to object deformation.

The phase distribution after deformation can be obtained as

$$\phi' = \phi + \Phi = \arctan\left(\frac{I_{a1} - 3I_{a2} + I_{a3} + I_{a4})}{I_{a1} + I_{a2} - 3I_{a3} + I_{a4}}\right) \tag{4}$$

The fringe locus function Φ extracted by subtracting Eq. (2) from Eq. (4) is related to the out-of-plane deformation (w) for normal illumination and observation condition as [1]

$$\Phi = \frac{4\pi}{\lambda}w \tag{5}$$

where λ is the wavelength.

The phase distribution, Φ is the wrapped or modulo 2π phase map, which range from $-\pi$ to π requires unwrapping. The evaluated phase Φ will have errors if $\alpha \neq \pi/2$ as assumed. This error is algorithm dependent. Other 3- and 4-step algorithms, given below, can also be used [11]

$$\Phi = \arctan\left(\frac{I_1 - 2I_2 + I_3}{I_1 - I_3}\right) \tag{6}$$

$$\Phi = \arctan\left(\frac{I_4 - I_2}{I_1 - I_3}\right) \tag{7}$$

We represent the 4-step algorithm in Eq. (2) as 4-step A and the algorithm in Eq. (7) as 4-step B. Fig. 2 shows the simulated