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Two-wavelength microscopic speckle interferometry using colour CCD camera

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ABSTRACT

Single wavelength microscopic speckle interferometry is widely used for deformation, shape and non-destructive testing (NDT) of engineering structures. However the single wavelength configuration fails to quantify the large deformation due to the overcrowding of fringes and it cannot provide shape of a specimen under test. In this paper, we discuss a two wavelength microscopic speckle interferometry using single-chip colour CCD camera for characterization of micro-samples. The use of colour CCD allows simultaneous acquisition of speckle patterns at two different wavelengths and thus it makes the data acquisition as simple as single wavelength case. For the quantitative measurement, an error compensating 8-step phase shifted algorithm is used. The system allows quantification of large deformation and shape of a specimen with rough surface. The design of the system along with few experimental results on small scale rough specimens is presented.

Keywords : Microscopic speckle interferometry, two-wavelength, colour CCD, deformation, shape, NDT

1. INTRODUCTION

Digital speckle pattern interferometry (DSPI) / TV holography (TVH)¹⁻⁹ and Digital shear speckle pattern interferometry (DSSPI) / TV shearography (TVS)^{10,11} are two independent optical techniques widely for optical metrology of engineering structures. TVH is sensitive to displacement whereas TVS is sensitive to displacement gradient. Single wavelength TVH with phase shifting facility is widely used for deformation measurements and NDT of engineering structures. But, if the deformation is large it results in overcrowding of fringes, then it is difficult to quantify such data using the single wavelength. Usually, the speckle de-correlation sets a limit for quantifying the large deformation. And also single wavelength TVH cannot generate shape of the test object. These problems can be eliminated using a 2λ -method¹²⁻²³. In this method, the phases measured at two different wavelengths (λ_1 and λ_2) are subtracted to generate phase at an effective wavelength. This approach desensitizes the measurement by synthetically increasing the wavelength. Thus it can convert the high frequency crowded fringes at single wavelength to low frequency less number of fringes at effective wavelength ($A = \lambda_1\lambda_2 / |\lambda_1 - \lambda_2|$), which then can be quantified easily using a conventional phase unwrapping algorithm. In this work, we demonstrate the use of multiple wavelengths in microscopic TV holography using color CCD camera for optical inspection of micro-specimens. Here, we use colour CCD which makes the data acquisition as simple as single wavelength case. The experimental results on a small scale samples for deformation, shape and NDT are presented.

2. TWO-WAVELENGTH MICROSCOPIC SPECKLE INTERFEROMETER

The schematic of the multiple-wavelength microscopic speckle interferometric system is depicted in Fig. 1. A frequency doubled Nd:YAG ($\lambda_1 = 532$ nm, 50 mW) and He-Ne ($\lambda_2 = 632.8$ nm, 20 mW) CW lasers are used in the system. The intensities of the beams are controlled using variable neutral density (VND) filters. The beams are expanded using a spatial filtering (SF) setup and collimated using a 150 mm focal length lens (CL). An iris in front of CL allows adjusting the collimated beam diameter. The collimated beams illuminate the specimen under study and a reference mirror (RM) via a beam splitter (BS2) simultaneously. The imaging system consists of a Thales-Optem zoom 125C long working distance

microscope (LDM) and a high JAI BB-500GE 2/3" GigE vision camera. It is a color progressive scan camera with 5 million pixels resolution. These are single-chip colour sensors which contain the primary colours red, green, and blue and are used in most single-chip digital image sensors used in digital cameras to create a color image. It has 2058(V) X 2456 (H) active pixels with a 3.45 μm square pixel. The camera is interfaced to PC with NI PCIe-8231 card. The phase shifter (PZT) is driven by an amplifier (A) which is interfaced to a PC with a NI DAQ6251 card. LABVIEW and MATLAB based programs suitable for colour CCD camera are developed for visualization of fringes, storing the phase shifted frames, and quantitative analysis of defects.

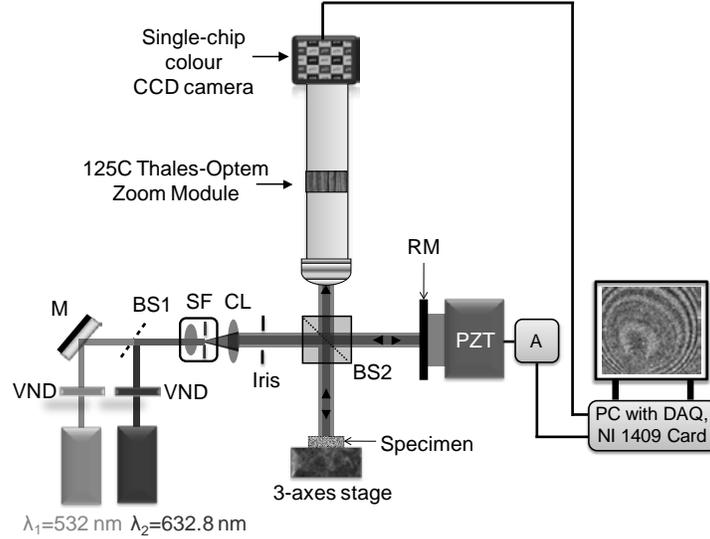


Fig. 1 Schematic of a two-wavelength microscopic speckle interferometric system.

3. THEORY

We store phase shifted frames at the wavelengths λ_i ($i = 1, 2$) before and after loading the specimen and their intensity distribution can be expressed as^{13,14}

$$B_{iN} = b(1 + \gamma \cos(\varphi_i^B + (N-1)\beta_i)) \quad (1)$$

$$A_{iN} = b(1 + \gamma \cos(\varphi_i^A + (N-1)\beta_i)) \quad (2)$$

where φ_i^B , $\varphi_i^A (= \varphi_i^B + \Delta\varphi_i)$ are the phases, B and A represent before and after deformation, $\Delta\varphi_i$ is the deformation phase, N is the number of phase shifted frames, and β_i is the phase shift for λ_i given by $\beta_i = (\lambda_2/\lambda_i) \pi/2$. While the phase step produced at any wavelength by a PZT can be set at 90° , the same motion of the PZT introduces a phase-step error at the other wavelength. We calibrate the PZT for phase step value $\beta_1 = 90^\circ$ at $\lambda_1 = 532$ nm. Hence $\beta_2 = (\lambda_2/\lambda_1) 90^\circ = 107^\circ$ for $\lambda_2 = 632.8$ nm. This error can be compensated by using 8-step algorithm which has a $\pm 20\%$ tolerance for phase shift error^{13,14}.

Using the 8-phase step algorithm, the speckle phase distribution before and after loading the object can be written in terms of an arctan function as^{13,14}

$$\varphi_i^B = \tan^{-1} \left(\frac{-B_{1i} - 5B_{2i} + 11B_{3i} + 15B_{4i} - 15B_{5i} - 11B_{6i} + 5B_{7i} + B_{8i}}{B_{1i} - 5B_{2i} - 11B_{3i} + 15B_{4i} + 15B_{5i} - 11B_{6i} - 5B_{7i} + B_{8i}} \right) \quad (3)$$

$$\varphi_i^A = \tan^{-1} \left(\frac{-A_{1i} - 5A_{2i} + 11A_{3i} + 15A_{4i} - 15A_{5i} - 11A_{6i} + 5A_{7i} + A_{8i}}{A_{1i} - 5A_{2i} - 11A_{3i} + 15A_{4i} + 15A_{5i} - 11A_{6i} - 5A_{7i} + A_{8i}} \right) \quad (4)$$

Since the evaluated individual wrapped phase maps φ_i^B , and φ_i^A are random distributions, no fringes can be observed.

The deformation at single wavelength can be obtained using the equation^{13,14}

$$\Delta\varphi_i = \varphi_i^A - \varphi_i^B = \frac{4\pi}{\lambda_i} w \quad (5)$$

where w is out-of-plane deformation. In 2λ -method, the single wavelength deformation phases $\Delta\varphi_1, \Delta\varphi_2$ corresponding to λ_1, λ_2 are subtracted to yield an effective wavelength phase which is governed by the following equation^{13,14}

$$\Phi = \Delta\varphi_1 - \Delta\varphi_2 = \frac{4\pi}{\Lambda} w \quad (6)$$

where, $\Lambda = (\lambda_1\lambda_2 / |\lambda_1 - \lambda_2|)$ is an effective wavelength. For $\lambda_1 = 532$ nm, $\lambda_2 = 632.8$ nm, the $\Lambda = 3.34$ μm . The sensitivity of our two-wavelength measurement system is $\Lambda/2$ (1.67 μm) per fringe.

The shape of an object can be obtained using the equation^{13,14}

$$\Phi = \varphi_1 - \varphi_2 = \frac{4\pi}{\Lambda} z \quad (7)$$

4. RESULTS

To demonstrate our system for NDT, we have carried out experiments on a flat 4 X 3 mm² on a specimen with a simulated defect in 1 mm² area. The specimen surface as well as the reference mirror is simultaneously illuminated with the collimated green (λ_1) and red (λ_2) beams via the beam splitter (BS2). The object and reference waves are recombined at the colour CCD plane. First, 8 phase shifted frames in the initial state of the object are stored. The sample is applied external pressure load and subsequent 8 phase shifted frames are similarly stored. The real-time colour fringe pattern is shown in Fig. 2(a). The colour phase shifted patterns stored by simultaneously illumination of are then decomposed in to its monochromatic components in MATLAB. The speckle patterns at single wavelength before and after loading are subtracted to generate speckle correlation fringes at λ_1, λ_2 and are shown in Figs. 2(b), and 2(c) respectively. The speckle phases at individual wavelengths are calculated using 8-step method. The deformation phase maps generated using Eq.(3) at λ_1 and λ_2 are shown in Figs. 3(a) and 3(b), respectively. These phase maps show that the defect that results in overcrowding of fringes. Because of the large deformation and high frequency of the wrapped phase, quantifying the data is difficult. So the single wavelength data fails to quantify such defects.

But, the 2λ -method helps to overcome such problems associated with single wavelength data. In 2λ -method, the wrapped phases at λ_1 (Fig. 3(a)) and λ_2 (Fig. 3(b)) are subtracted to generate an effective wavelength phase at $\Lambda = 3.34$ μm (Fig. 3(c)) which clearly shows fringes in the defect location. The effective wrapped phase is unwrapped and scaled using Eq.(4). The 3-D plot in Fig. 3(d) clearly shows the enhanced defect. To demonstrate our system for deformation and shape, we have carried out experiments on a MEMS pressure sensor with a 1 mm² square membrane at the center. The sample is simultaneously illuminated by multiple wavelengths. Eight phase shifted frames are stored in the initial state of the membrane. Then pressure is applied externally in a controlled manner to deflect the membrane. Similarly, another set of eight phase shifted frames are stored after loading. The shape analysis evaluated using Eq.(7) is shown in Fig.4. The membrane is projected about ~ 1.67 μm above the substrate. The large deformation evaluated using Eq.(6) is shown in Fig.5. The maximum deformation is ~ 5.34 μm , which corresponds to ~ 20 fringes at 532 nm.

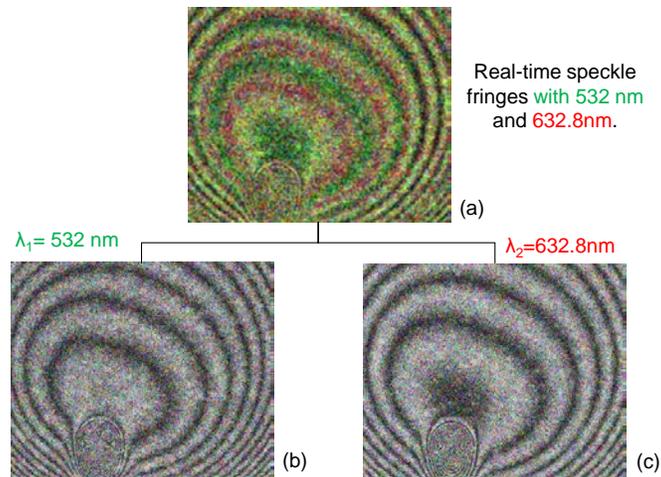


Fig. 2 Defect analysis using single wavelength method: (a) Real-time colour fringes, Fringes (b) at λ_1 (532 nm), (c) at λ_2 (632.8 nm).

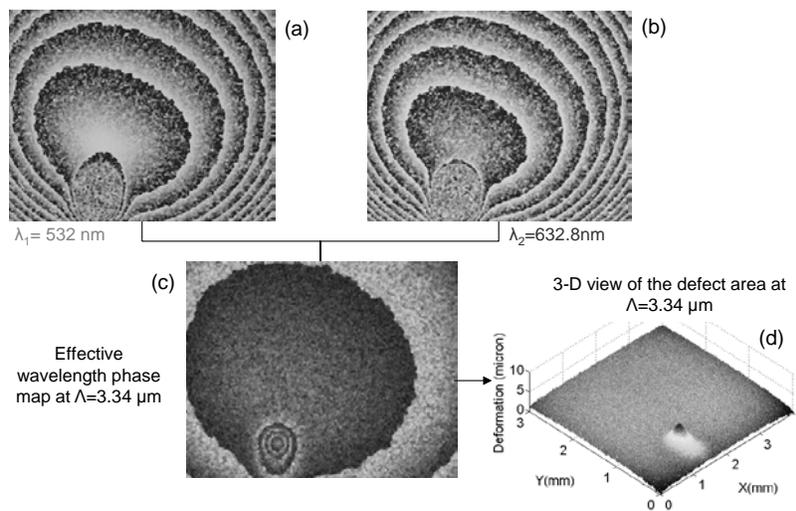


Fig. 3 Defect analysis using 2λ -method: phase map (a) at λ_1 (532 nm), (b) at λ_2 (632.8 nm), (c) at $\Lambda = 3.34 \mu\text{m}$, and (d) 3-D profile at Λ .

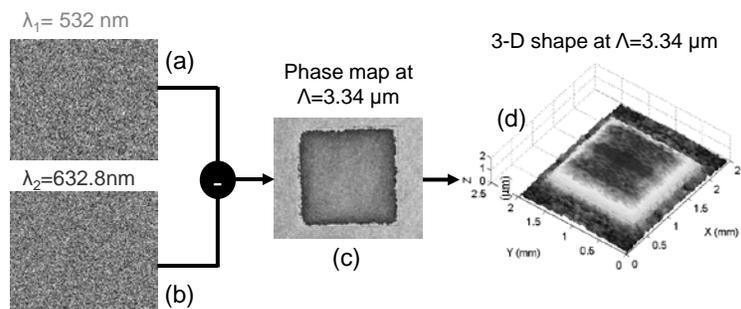


Fig. 4 Shape analysis using 2λ -method: phase map (a) at $\lambda_1 = 532 \text{ nm}$, (b) at $\lambda_2 = 632.8 \text{ nm}$, (c) at $\Lambda = 3.34 \mu\text{m}$, and (d) 3-D shape at Λ .

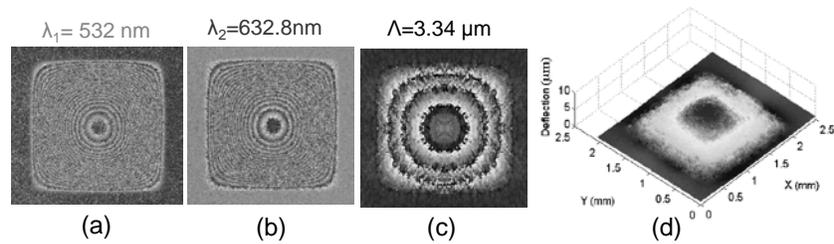


Fig. 5 Large deformation analysis using 2λ -method: phase map (a) at $\lambda_1 = 532$ nm, (b) at $\lambda_2 = 632.8$ nm, (c) at $\Lambda = 3.34$ μm , and (d) 3-D deformation profile at Λ .

5. CONCLUSIONS

A multiple wavelength microscopic speckle interferometric system using a single chip color CCD camera is demonstrated for deformation, shape and NDT of microsystems. The use of color CCD camera makes the data acquisition process as simple as in single wavelength case and thus it makes the measurement faster compared to sequential illumination method. The setup can be operated to work at single wavelength, giving a high sensitive measurement with a limited range, or with two wavelengths simultaneously, giving less sensitive measurements with an extended range. The system will find applications in optical inspection of microsystems in industry.

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