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Use of two wavelengths in microscopic TV holography for nondestructive testing

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Abstract. Single wavelength TV holography is a widely used whole-field noncontacting optical method for nondestructive testing (NDT) of engineering structures. However, with a single wavelength configuration, it is difficult to quantify the large amplitude defects due to the overcrowding of fringes in the defect location. In this work, we propose a two wavelength microscopic TV holography using a single-chip color charge-coupled device (CCD) camera for NDT of microspecimens. The use of a color CCD allows simultaneous acquisition of speckle patterns at two different wavelengths and makes the data acquisition as simple as that of the single wavelength case. For the quantitative measurement of the defect, an error compensating eight-step phase-shifted algorithm is used. The design of the system and a few experimental results on small-scale rough specimens are presented. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.53.11.110501]

Keywords: TV holography; color charge-coupled device; nondestructive testing; two-wavelength; phase shifting.

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1 Introduction

Nondestructive testing (NDT) of mechanical elements is an important requirement in many industrial applications. TV holography (TVH)^{1–6} and TV shearography (TVS)^{7,8} are two independent optical techniques widely used by the industry as a prominent tool for NDT. TVH is sensitive to out-of-plane deformation, whereas TVS is sensitive to the gradient of deformation. Any defect on the object will induce an anomaly in the fringe pattern in and around the defect location. For quantitative measurement of the defect, the generation of a phase map using a phase evaluation approach is necessary. Single wavelength TVH with a phase shifting facility is widely used for deformation measurements and NDT of engineering structures. However, if the deformation in the defect location results in overcrowding of the fringes, it is difficult to quantify such defects using single wavelength data. Usually, the speckle de-correlation sets a limit for quantifying a large deformation. This problem can be eliminated

using a two-wavelength method (2 λ -method).^{9–13} In this method, deformation phases measured at two different wavelengths (λ_1 and λ_2) are subtracted to generate a phase at an effective wavelength. The shape of the test object can also be obtained using this method.^{9–12} This approach desensitizes the measurement by synthetically increasing the wavelength. Thus, it can convert the high frequency crowded fringes at single wavelength to a low frequency with fewer fringes at the effective wavelength ($\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$), which can easily be quantified using a conventional phase unwrapping algorithm. This phenomenon is used here. In this work, we demonstrate the use of two wavelengths in microscopic TV holography for NDT of microspecimens. The 2 λ -method^{10–17} can be implemented in two different modes: (1) sequential illumination mode^{10–12} using a monochrome camera and (2) simultaneous illumination mode using a color charge-coupled device (CCD) camera.^{13,14} Here, we use the second approach which makes the data acquisition as simple as that of the single wavelength case and allows for faster measurement compared to the sequential mode. The experimental results on a small rough sample with a defect subjected to an external pressure load are presented.

2 Two-Wavelength Microscopic TV Holography Set-Up

The schematic of the two-wavelength microscopic TV holographic system is depicted in Fig. 1. A frequency doubled Nd:YAG ($\lambda_1 = 532$ nm, 50 mW, vertical polarization, coherence length ~ 60 mm) and He-Ne ($\lambda_2 = 632.8$ nm, 20 mW, vertical polarization, coherence length ~ 30 mm) CW lasers are used in the system. The intensities of the beams are controlled using variable neutral density filters. The beams are expanded using a spatial filtering 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 simultaneously illuminate the specimen under study and a reference mirror via a beam splitter (BS2). 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 5×10^5 pixels resolution. These are single-chip color sensors which contain the primary colors red, green, and blue. These colors are used in most single-chip digital cameras to create a color image. It has 2058(V) $\times$ 2456 (H) active pixels with a $3.45\text{-}\mu\text{m}$ square pixel. The camera is interfaced to a PC with an NI PCIe-8231 card. The phase shifter (PZT) is driven by an amplifier (A) which is interfaced to a PC with an NI DAQ6251 card. LABVIEW and MATLAB[®]-based programs suitable for color CCD cameras are developed for visualization of fringes, storing the phase-shifted frames, and quantitative analysis of defects.

3 Theory of 2 λ -Method

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^{1–3}

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

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Fig. 1 Schematic of a two-wavelength microscopic TV holography system.

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

where φ_i^B , $\varphi_i^A (= \varphi_i^B + \Delta\varphi_i)$ are the phases, B and A represent the before and after deformations, $\Delta\varphi_i$ 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 a phase step value $\beta_1 = 90^\circ$ at $\lambda_1 = 532$ nm. Hence, $\beta_2 = (\lambda_2/\lambda_1)90^\circ = 107^\circ$ deg for $\lambda_2 = 632.8$ nm. This error can be compensated by using eight-step algorithm which has a $\pm 20\%$ tolerance for phase shift error.^{10,14} The speckle phase distributions φ_i^B , and φ_i^A are obtained using an eight-step algorithm.^{10,11} The deformation at a single wavelength can be obtained using the equation

$$\Delta\varphi_i = \varphi_i^A - \varphi_i^B = \frac{4\pi}{\lambda_i} w, \quad (3)$$

where w is the out-of-plane deformation. In the 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:^{10,11}

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

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.

4 Experimental Results

We have carried out experiments on a flat 4×3 mm² specimen with a simulated defect in a 1 mm² area. The defect is a blind hole in the 1 mm² area. The sample is mounted on a pressure housing and loading unit.¹⁷ First, white light illumination is used to focus the specimen onto the CCD by adjusting the fine focusing knob in the LDM. The specimen surface as well as the reference mirror are 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 color CCD plane. First, eight phase-shifted frames in the initial state of the object are stored. An external pressure load is applied to the sample and the subsequent eight phase-shifted frames are similarly stored. The real-time color fringe pattern is shown in Fig. 2(a). The color phase-shifted patterns are stored by simultaneous illumination of the area then decomposing it into its monochromatic components in MATLAB. The speckle patterns at a single wavelength before and after loading are subtracted to generate speckle correlation fringes at λ_1 (532 nm), λ_2 (632.8 nm) and are shown in Figs. 2(b), and 2(c), respectively. The speckle phases at individual wavelengths are calculated using an eight-step method.^{10,11} The deformation phase maps generated using Eq. (3) at λ_1 and λ_2 are shown in Figs. 2(d) and 2(e), respectively. A median filtering with a 3×3 window is used to reduce the noise associated with raw phase maps. These phase maps show the defect which results in overcrowding of the fringes. The three-dimensional (3-D) deformation plots at λ_1 and λ_2 are shown in Figs. 2(f), and (g). Because of the large deformation and high frequency of the wrapped phase, quantifying the data is difficult. Thus, single wavelength data fail to quantify such defects.

As discussed in Sec. 3, the 2λ -method helps to overcome such problems associated with single wavelength data. In the 2λ -method, the phases (wrapped between $-\pi$ and π) at individual wavelengths (λ_1 and λ_2) are subtracted resulting in a phase wrapped between -2π and 2π . It is re-wrapped between $-\pi$ and π to obtain an effective wavelength (Λ) phase. The wrapped phases at λ_1 [Fig. 2(d)] and λ_2 [Fig. 2(e)] are subtracted to generate an effective wavelength phase at $\Lambda = 3.34$ μm [Fig. 3(a)], which clearly shows fringes in the defect location. The phase map at the effective wavelength is then unwrapped and scaled using Eq. (4). The

Fig. 2 Defect analysis using single wavelength method: (a) real-time color fringes, fringes (b) at λ_1 (532 nm), (c) at λ_2 (632.8 nm), phase maps (d) at λ_1 , (e) at λ_2 , and three-dimensional (3-D) plots (f) at λ_1 , (g) at λ_2 .

Fig. 3 Defect analysis using 2λ -method: (a) effective wavelength phase map at $\lambda = 3.34 \mu\text{m}$, (b) 3-D profile at λ , (c) line scan profiles across the defect area along y -axis. A DC shift is given to profiles B and C, for clarity.

3-D plot in Fig. 3(b) clearly shows the enhanced defect. The line scans' profiles across the defect along the y -axis are shown in Fig. 3(c). The profiles A and B are obtained from the single wavelength phases shown in Figs. 2(d) and 2(e), respectively. They do not show the defect, whereas the profile-C obtained from the effective wavelength phase [Fig. 3(a)] clearly shows the defect. Profile-C is noisy compared to profiles A and B due to the subtraction of phases measured at two different wavelengths.^{10,11}

5 Conclusions

A two-wavelength microscopic TV holographic system using a single-chip color CCD camera is demonstrated for quantifying large amplitude defects where a single wavelength configuration fails. The use of a color CCD camera makes the data acquisition process as simple as that of the single wavelength case, and it makes the measurement faster compared to the sequential illumination method.

The setup can be operated to work at a single wavelength, yielding a highly sensitive measurement with a limited range, or with two wavelengths simultaneously, yielding less sensitive measurements with an extended range. This method makes it possible to quantify large amplitude defects and can simultaneously generate the initial shape of an object under test. The system will find applications in NDT for the mechanical elements in industry.

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