SPECKLE NOISE REDUCTION IN FULL-FIELD STRESS ANALYSIS BY INTERFEROMETRIC PHASE-STEPPING IMPLEMENTATION OF THE PHOTOELASTIC-COATING METHOD

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ABSTRACT:

1. INTRODUCTION

An interferometric phase-shifting realization of the photolastic-coating method is an effective approach to separate the stress components over the tested specimen due to its easier and faster implementation in comparison with the oblique-incidence method, the strip coating method and the strain gage separation method. For the purpose, a series of six photoelastic fringe patterns are recorded at different preliminary known orientations of the polarization elements in a circular polariscope to build both isochromatic and isoclinic phase maps which give the loci of points with a constant difference of principal stresses and constant principal stress direction respectively. In addition, holographic recording of four fringe patterns is applied for retrieval of isopachic fringes which give the sum of principal stresses. If a two-load phase-shifting technique is applied for unambiguous phase retrieval of all photoelastic parameters required for full-field stress analysis, the number of the fringe patterns used for the final calculation of the stress components doubles. This increases the requirements set on the accuracy of the phase retrieval. Therefore the reliable stress separation crucially depends on the signal-to-noise ratio in the recorded fringe patterns. The easiest way to perform a combined polariscopic and holographic measurement for full-field stress analysis is to use a laser light source. However, the speckle noise at coherent illumination violates the requirement for high signal-to-noise ratio in the recorded patterns and worsens the accurate phase estimation and unwrapping. To answer the question how the speckle noise affects the phase retrieval of isochromatics, isoclinics and isopachics we solved two tasks in the presented report: i) modelling of the phase-shifting photoelastic measurement based on calculation of the complex amplitudes in a Mach-Zender interferometer combined with a circular polariscope; ii) comparison of different denoising algorithms with and without normalization by processing simulated and experimental fringe patterns. The latter were recorded at pure tensile load for PhotoStress coated samples with different mechanical stress concentrators.

2. INTERFEROMETRIC PHOTOELASTIC MEASUREMENT AT LASER LIGHT ILLUMINATION

The measurement is performed in reflection mode using a Mach-Zender interferometer combined with a circular polariscope. A linearly polarized laser light is divided into object and reference beams. When the shutter in the reference beam is closed, the system operates as a circular polariscope for photoelastic measurement of isochromatics and isoclinics. The laser light passes through a quarter-wave plate $Q_{\pi/4}$, a birefringent specimen $R_{\delta,\theta}$, a second quarter-wave plate Q_γ and an analyzer A_β . When the shutter is open, both beams interfere on the CCD target. The Jones matrix for the specimen depends on the phase retardations δ_1 and δ_2 along the principal directions of the specimen. The combined measurement permits to extract both difference and sum of the principal stresses σ_1 and σ_2 as

$$\delta_d = \delta_1 - \delta_2 = 2\pi \frac{Ct}{\lambda}(\sigma_1 - \sigma_2) , \quad \delta_s = \delta_1 + \delta_2 = 2\pi \frac{Dt}{\lambda}(\sigma_1 + \sigma_2) \tag{1}$$

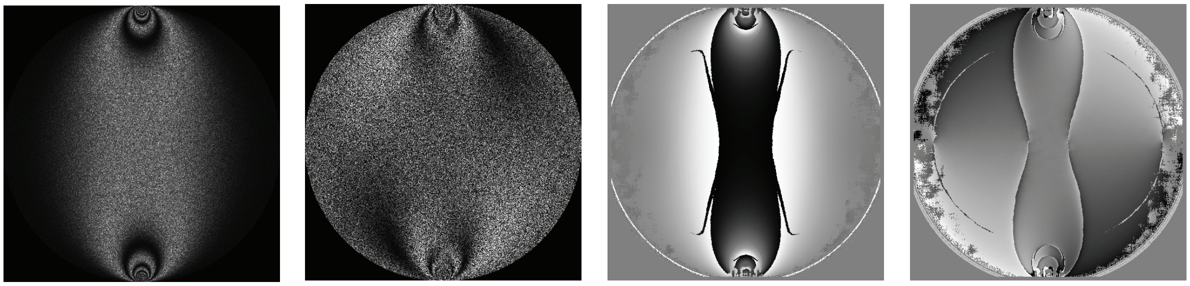
where t is the thickness of the specimen, C and D are its optical constants, and λ is the wavelength. The Jones vector of light at the system output is given by

$$E = \begin{bmatrix} E_{II} \\ E_{\perp} \end{bmatrix} = A_\beta Q_\gamma R_{\delta,\theta} Q_{\pi/4} P_\alpha \tag{2}$$

where the values of the angles α, β, γ for the recorded six isochromatic and four isopachic patterns are taken from [1]. The signal-dependent noise model is assumed for the speckle noise. It is modeled as a delta-correlated circular Gaussian process in the location of the specimen with the Jones vector of light just after reflection from the specimen given by

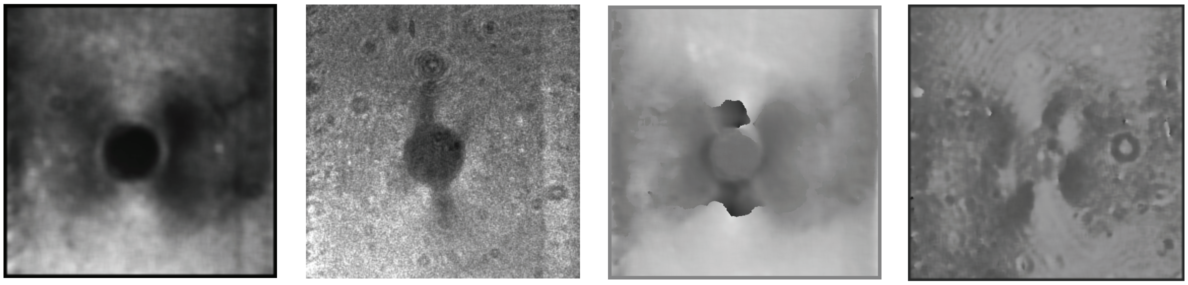
$$E_{\delta,\theta} = \begin{bmatrix} \mu_x + i\nu_x \\ \mu_y + i\nu_y \end{bmatrix} = \begin{bmatrix} (a_{11}a_{sp} - a_{12}b_{sp}) + i(a_{12}a_{sp} + a_{11}b_{sp}) \\ (a_{21}a_{sp} - a_{22}b_{sp}) + i(a_{22}a_{sp} + a_{21}b_{sp}) \end{bmatrix} \tag{3}$$

where the coefficients $a_{11}, a_{12}, a_{21}, a_{22}$ depend on the angles α, β, γ, and a_{sp}, b_{sp} are calculated as $N(0{,}0.5)$ random numbers ($N(a, s^2)$ is an independent Gaussian variable with a mean a and variance s^2). The simulated speckled fringe patterns for a polariscopic measurement at $\alpha = \pi/2, \beta = \pi/4, \gamma = 0$ and a holographic measurement at $\alpha = \beta = 0, \gamma = 0$ for an epoxy resin disk with a radius 21.2 mm, thickness 6 mm, $C = 52.1\times10^{12}\mathrm{m}^2\mathrm{N}^{-1}$ and $D = 217.3\times10^{12}\mathrm{m}^2\mathrm{N}^{-1}$ under concentrated diametral compression are shown in Fig.1 a and b. The wavelength is 532 nm. The applied forces for a two-load measurement are 100 N and 105 N respectively. The simulated image size is 512×512 pixels, and the spacing of the interferometric pattern is 0.6 mm. The simulation is especially chosen to correspond to the case of very large variation of stresses over the specimen surface. This put stringent requirements on the accuracy of the phase retrieval. Figure 1 c and d depicts the isochromatic and isoclinic phase maps which are calculated from the filtered with a Jones-Stein filter (size of the window 7×7) fringe patterns. We see comparatively satisfactory result over the disk surface with erroneous regions on its periphery. However, accuracy is much lower for the isopachics, which requires more sophisticated denoising algorithms.



(a) (b) (c) (d)

Figure 1 – (a) fringe pattern at $\alpha = \pi/2, \beta = \pi/4, \gamma = 0$; (b) fringe pattern at $\alpha = \beta = 0, \gamma = 0$; (c) wrapped phase map for isochromatics; (d) isoclinic phase map (simulation).



(a) (b) (c) (d)

Figure 2 - (a) filtered fringe pattern at $\alpha = \pi/2, \beta = \pi/4, \gamma = 0$; (b) filtered fringe pattern at $\alpha = \beta = 0, \gamma = 0$; unwrapped isochromatic (c) and isopachic (d) phase maps after denoising (experiment).

Denoising of the fringe patterns gave substantial improvement in accuracy of the experimental isochromatic, isoclinic and isopachic phase retrieval. The experiments were made for PhotoStress coated samples with different stress concentrators at pure tensile load using a Mach-Zender interferometer combined with a circular polariscope with a DPSS laser. Figure 2 a and b depicts filtered fringe patterns obtained from the polariscopic and the holographic measurement for a sample of window security film with a hole as a stress concentrator. Figure 2 c and d compares the unwrapped phase map of isochromatics and isopachics calculated from filtered with a Jones-Stein filter (size of the window 7×7) fringe patterns. As it can be seen, a comparatively good quality of phase retrieval is achieved also in the case of isopachics. To compare different denoising approaches, the quality of the phase retrieval after denoising was characterized by the histograms of fluctuations in the unwrapped phase maps obtained for the three photoelastic parameters as well as by one-dimensional profiles of the calculated principal stresses.

3. REFERENCES

1. Lei, Z., Yun, H., Yun, D., Kang, Y. (2007) Numerical analysis of phase-stepping interferometric photoelasticity for plane stress separation, *Opt. Las. Eng.* 45, 77–82