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Application of Phase-Shifting Method in Speckle Interferomtery to Measurement of Micro-Scale Displacement

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Abstract Speckle interferometry with phase-shifting method has been applied to measurement of micro-scale displacement through optical signal processing. Four-step phase-shifting method by PZT is used to measure out-of-plane displacement in spot-welded cantilever and results of optical experiments are comparable to those of FEM. Phase-shifting method using Fourier transform by PZT is applied to measurement of in-plane displacement on rectangular steel plate with a circular hole. The results of optical experiment agree well with theoretical calculation. New phase-shifting method in speckle interferometry has been implemented with a quarter wave plate. In-plane displacement of specimen is measured by the new phase-shifting method. Results of optical experiment show that the quarter wave plate can be used for phase-shifting method that is cheap and easy to use in speckle interferometry.

Keywords: Speckle Interferometry, Phase-Shifting Method, Measurement of Displacement, Quarter Wave Plate

1. Introduction

Optical signal processing has been used in many areas of science and technology. Speckle interferometry is an optical technique to measure displacement of a specimen by use of optical signal processing (Cloud, 1995). Speckle interferometry can perform whole-field measurement for displacement of a specimen due to two-dimensional signal processing of light. Also it can perform non-contact measurement because of transmission or reflection of light on a specimen. In speckle interferometry, displacement of a specimen is measured through phases of interference fringe patterns. Phase shift method (PSM) used in speckle interferometry is an engineering method to extract the phases caused by displacement (Creath, 1985; Petzing and Tyrer, 1998). PSM is realized conveniently with piezoelectric transducer (PZT) in an optical system (Lanza di Scalea et al., 1998). In this paper, three different kinds of phase-shifting methods are used in speckle interferometry to measure in-plane displacement and out-of-plane displacement of specimens. The first one is to use 4-step phase-shifting method (4-step PSM) implemented with PZT in order to measure out-of-plane displacement. The second one is to use phase shifting method with Fourier transform (PSM/FT) implemented with PZT in order to measure in-plane displacement. However, the third one does not use PZT, but it uses a quarter wave plate to implement PSM. The quarter wave plate for implementation of PSM is much cheaper than PZT. The PSM by the quarter wave plate is used to measure in-plane displacement.

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2. Speckle Interfermetry Using 4-Step PSM

Fig. 1 is the optical system of speckle interferometry using 4-step PSM for measuring out-of-plane displacement. 4-step PSM is to get the information of out-of-plane displacement contained in interferometric fringe patterns. The reference plane in Fig. 1 is moved by PZT such that relative phase differences between the specimen and the reference plane, α, becomes 0, $\pi/2$, π, $3\pi/2$ radians and the phase differences generate the fringe patterns.

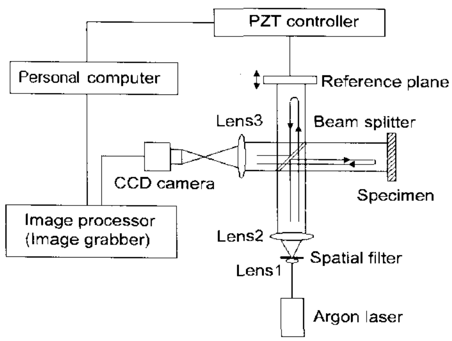


Fig. 1 Optical system to measure out-of-plane displacement using speckle interferometry with 4-step phase-shifting method

Through the analysis of the fringe patterns, the wrapped phase map caused by the out-of-plane displacement of specimen, $\phi(x,y)$, is calculated,

$$\phi(x,y) = \tan^{-1}\left(\frac{I_4 - I_2}{I_1 - I_3}\right) \quad (1)$$

where I_1, I_2, I_3 and I_4 are the light intensities of fringe patterns at $\alpha=0$, $\pi/2$, π, $3\pi/2$ radians, respectively (Baek et al., 2003). The phase map has lots of speckle noises, so that an image processing algorithm of Gaussian blur available in Photoshop is used to suppress the noises. The phase map has the discontinuous phase at every 2π radians. But continuous unwrapped phase map is acquired by use of the phase unwrapping process and the out-of-plane displacement of specimen can be obtained.

The specimen used in this optical experiment is 2 mm-thick cantilever made of steel plate. The cantilever plate is spot-welded on the rear side, so that the welded area is not visible. The shape and size of the specimen is shown in Fig. 2. The specimen is placed at the optical system in Fig. 1 and 4-step PSM is applied. The laser is Ar-laser with wavelength of 515nm. The fringe patterns of specimen at $\alpha=0$, $\pi/2$, π, $3\pi/2$ radians, respectively, are captured by CCD camera. The wrapped phase, ϕ, in eqn. (1) is obtained by use of the fringe patterns. The phase, ϕ, is processed by Gaussian blur algorithm and shown in Fig. 3. As in Fig. 3, the wrapped phase map of the spot welded cantilever plate shows a phase reversal near the welded area. Figure 4 shows wrapped and unwrapped phase distributions along line

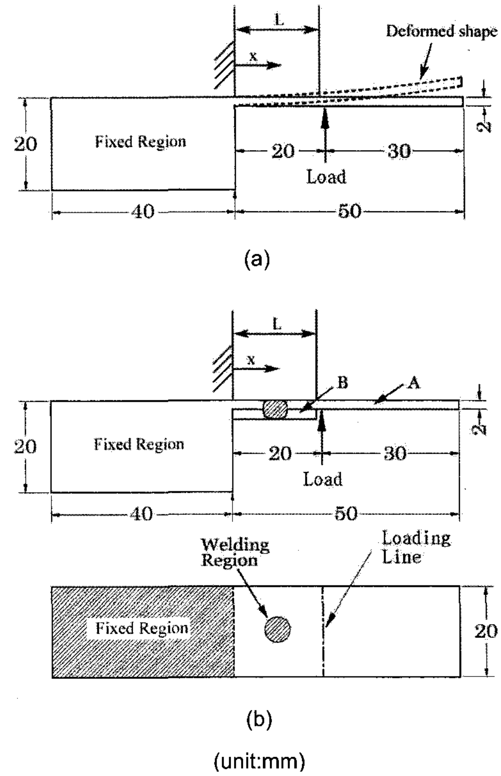


Fig. 2 Dimensions of the specimen used for measurement of out-of-plane displacement. (a) normal cantilever without spot weld (before weld), (b) spot welded cantilever (after weld)

A-A of Fig. 3. As shown in Fig. 5 for 3-D view of the unwrapped phase image (Ghiglia and Pritt, 1998), it is clearly seen that the displacement at the spot welded area is hump-shaped.

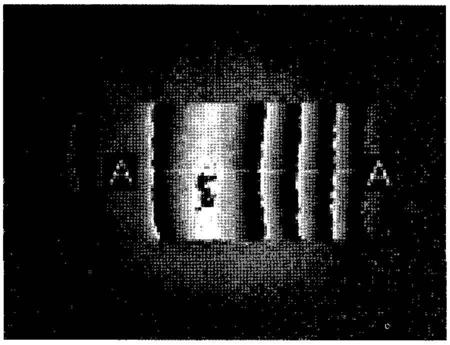


Fig. 3 Wrapped phase map of spot welded cantilever

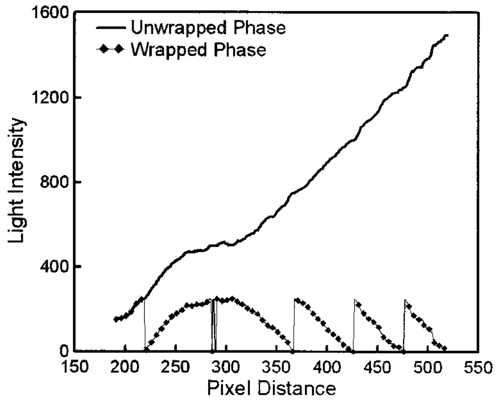


Fig. 4 Wrapped and unwrapped phase distribution along line A-A of Fig. 3.

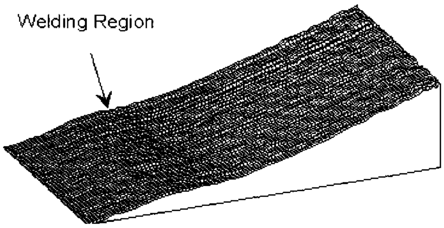


Fig. 5 3-D view of unwrapped phase map

Fig. 6 shows the distribution of out-of-plane displacement obtained from the specimen. The dotted line in Fig. 6 represents the theoretical displacement of normal cantilever plate in Fig. 2-(a), and the solid line represents the displacement of specimen along A-A line in Fig. 3 that are obtained from optical experiment with 4-step PSM. From the solid line, the micro-scale displacements, 0.582 μm, 1.183 μm, and 2.134 μm, are measured at 10 mm, 20 mm, and 30 mm from the fixed area of the specimen, respectively. Therefore, the speckle interferometry with 4-step PSM can measure the displacement of sub-micrometers in the specimen. Especially, the spot welded area that is not visible can be easily detected when speckle interferometry is used.

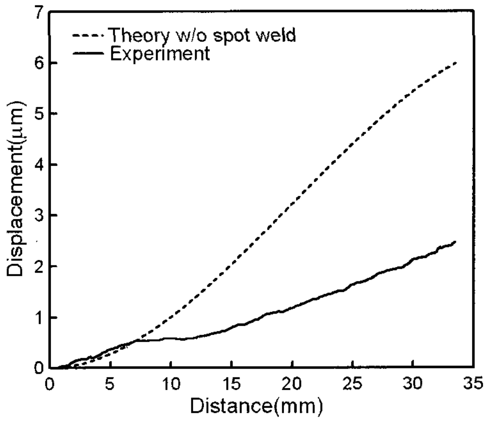


Fig. 6 Theoretical displacement of normal cantilever plate without spot welding in Fig. 2-(a) and displacement of spot-welded cantilever in Fig. 2-(b) obtained from optical experiment with 4-step PSM.

3. PSM/FT in Speckle Interferometry

This chapter describes optical technique to measure micro-scale displacement of specimen through directional Fourier transform applied to phase-shifting method in speckle interfrerometry (Morimoto et al., 1988). When two optical beams in speckle interferometry illuminate a specimen with in-plane displacement, these beams make interferometric fringe pattern. Several fringe patterns are generated by use of phase-shifting method implemented with PZT. The wrapped phase map caused by displacement, $\phi(x,y)$, can be calculated by use of directional Fourier transform taken with the fringe patterns as follows (Kim et al., 2005);

$$\phi(x,y) = -\tan^{-1}\left(\frac{\mathrm{Im}[F_\alpha(x,y:\omega_0)]}{\mathrm{Re}[F_\alpha(x,y:\omega_0)]}\right) \quad (2)$$

$F_\alpha(x,y:\omega_0)$ in eqn. (2) means directional Fourier transform and ω_0 represents fundamental frequency. In PSM/FT, only fundamental frequency component (ω_0=1) is used for the calculation of phase, so that the noises in the high frequency components caused by phase-shifting error can be eliminated.

Fig. 7 is the schematic diagram of optical experiment system for speckle interferometry by PSM/FT to measure micro-scale in-plane displacement. In Fig. 7, LA is a laser, PA is a pin-hole assembly, CL is a collimating lens, BS is a non-polarizing beam splitter, MR1 and MR2 are mirrors. SL is a specimen installed in a tensile loading device. The loading device applies tensile load to the specimen and causes in-plane displacement of specimen. PZT stage is a PZT-installed system and CNT is a control system of PZT. CCD is a CCD camera, and PC is a personal computer. BS is controlled by PZT for phase-shifting method in speckle interferometry. That is, BS is installed on PZT such that PZT moves the beam splitter toward the mirror 1. This movement makes optical path length difference between two beams onto the specimen. The fringe patterns on the specimen are saved in PC through CCD. The wrapped phase map, $\phi(x,y)$, is obtained with applying the saved patterns to directional Fourier transform of eqn. (2).

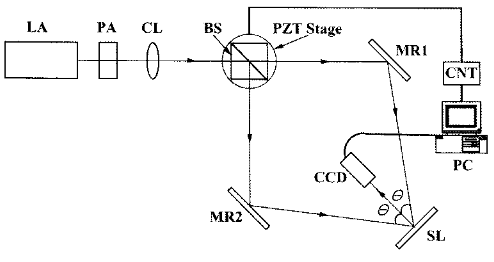


Fig. 7 Schematic diagram of optical experiment system for speckle interferometry by PSM/FT

The specimen for the optical experiment is a rectangular steel plate containing a circular hole at the center. Its size is 113 mm × 27.7 mm with 1.15 mm of thickness and diameter of the hole is 12 mm. The specimen is installed in a loading device that applies tensile load to the specimen in order to make in-plane displacement. The laser in the experiment is He-Ne laser with wavelength of 633 nm. Fringe patterns, $I(x,y:\alpha)$, are taken through CCD camera in Fig. 7. They consist of 32 patterns that are sequentially phase-shifted by PZT and are saved in PC. Phase shifting at each step is $\pi/16$ radian. Size of each fringe pattern is 640 × 480 with 8 bits brightness. $I(x,y:\alpha)$ contains lots of spatial noises caused in speckle interferometry, and these spatial noises can be suppressed through two-dimensional (2-D) Fourier filtering. To do it, 2-D Fourier transform, low pass filtering, and 2-D inverse Fourier transform are performed for each of the 32 fringe patterns. Directional Fourier transform is performed with low pass filtered fringe patterns. A mixed radix fast Fourier transform (MRFFT) is used for 2-D Fourier filtering and directional Fourier transform (Morimoto and Fujisawa, 1994). Only $F_\alpha(x,y:\omega_0)$ at ω_0=1 is taken to calculate the wrapped phase as in eqn. (2). The wrapped phases, ϕ, of specimen is shown in Fig. 8. The wrapped phase is unwrapped through unwrapping algorithm and the micro-scale in-plane displacement of specimen along A-A, B-B, and C-C lines in Fig. 8 is shown in Fig. 10. For comparative purpose, the specimen is analyzed by FEM software (ANSYS). The ANSYS discretization for one-quarter of the specimen is shown in Fig. 9. It uses 416 eight-node isoparametric elements and 1349 nodes. In the vicinity of the circular hole, the ANSYS model utilizes elements on the edge of the hole as small as 1.5° by 0.013r, where r is the radius of the circular hole. The results of ANSYS are shown with dotted lines in Fig. 10. As shown in Figs. 10, the results of the speckle experiment by PSM/FT agree well with those of ANSYS.

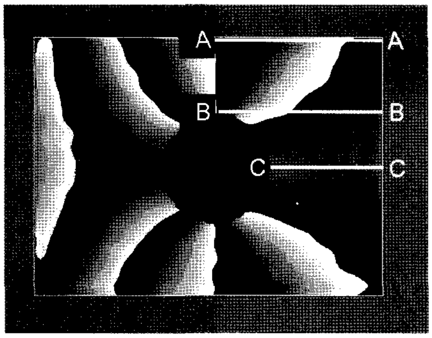


Fig. 8 Wrapped phase ϕ of rectangular steel plate containing a circular hole at the center

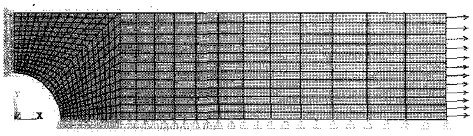
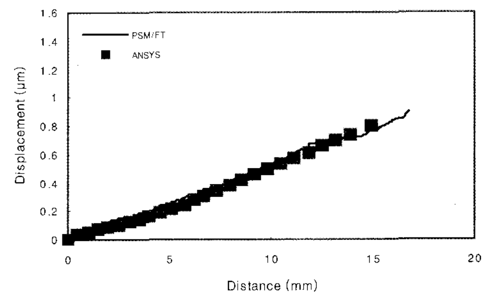


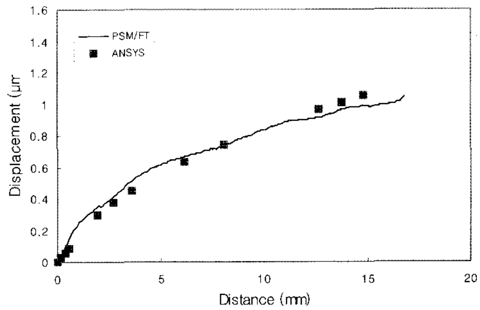
Fig. 9 ANSYS discretization of a quarter plate with a circular hole

4. PSM by Quarter Wave Plate in Speckle Interferometry

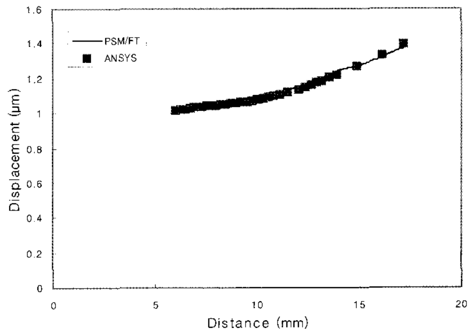
Phase-shifting method by PZT can measure conveniently displacement but PZT is an expensive electronic system. In this chapter, new phase-shifting method by quarter wave plate ($\lambda/4$ plate) that is cheap and easy to use is applied to measurement of displacement. Two optical beams with vertical polarization illuminate the specimen with in-plane displacement as in Fig. 11. In Fig. 11, LA is a laser, and SF is a spatial filter. BS is a beam splitter, MR is a mirror, QT is $\lambda/4$ plate, and PL is a polarizer. SL is a specimen installed in a loading device. CCD camera is connected to PC that is a personal computer with an image grabber. Let I_1, I_2, I_3 be the intensities of fringe patterns on the specimen at the angle of $\lambda/4$ plate, $\delta=\pi/2$, $\pi/4$, and 0 radian, respectively. The angle, θ, means the angle between of F-axis and horizontal axis in $\lambda/4$ plate as in Fig. 12. F-axis means a fast-axis and S-axis means a slow-axis in Fig. 12. When $\lambda/4$ plate is analyzed by Jones matrix and Jones calculus (Theocaris and Gdoutos, 1979), wrapped phase map of specimen, ϕ, caused



(a) Line A-A



(b) Line B-B



(c) Line C-C

Fig. 10 In-plane displacement along the specified lines indicated in Fig. 8 of rectangular steel plate containing a circular hole by experiment and ANSYS

by in-plane displacement of the specimen can be represented as follows (Kim et al., 2001);

$$\phi = \tan^{-1}\left(\frac{4I_2 - 2I_1 - I_3}{4I_2 - I_1 - 2I_3}\right) \tag{3}$$

Optical experiment is carried out to measure in-plane displacement of specimen using the optical system as in Fig. 11. In Fig. 11, the wavelength of laser is 515 nm. The material of $\lambda/4$

plate is quartz and it operates at the wavelength of laser. A steel plate is used as a specimen, which is 147 mm × 27.7 mm with thickness 1.15 mm. Tensile load is applied to the specimen by loading device. Images before and after loads are applied are captured by CCD camera and saved in PC, and the wrapped phase map is calculated as in eqn. (3). The wrapped phase is shown in Fig. 13. As seen in Fig. 13, it has lots of speckle noises, so that a median filtering algorithm available in Photoshop is applied to Fig. 13 in order to suppress the noises. The processed wrapped phase is in Fig. 14. After unwrapping process of Fig. 14, the in-plane displacement of specimen is obtained as in Fig. 15. The solid line is from optical experiment with $\lambda/4$ plate and the dotted line is expected values. There are jumps at the solid line. These are caused by phase jump of unwrapped phase from the wrapped phases at 2π, 4π, and 6π radians. As seen in Fig. 15, a quarter wave plate can be used for phase shifting method in speckle interferometry to measure micro-scale in-plane displacement.

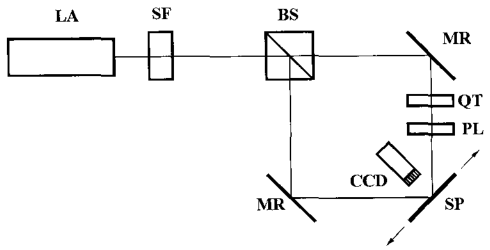


Fig. 11 Schematic diagram of optical system for PSM using quarter wave plate

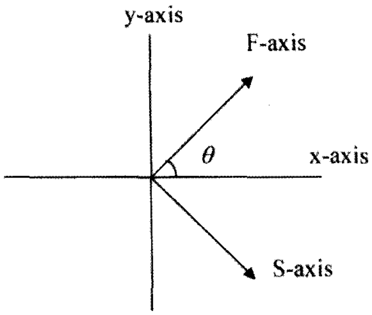


Fig. 12 Orientation of F-axis and S-axis in quarter wave plate

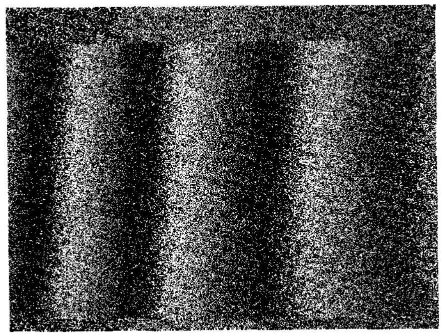


Fig. 13 Wrapped phase obtained by optical experiment

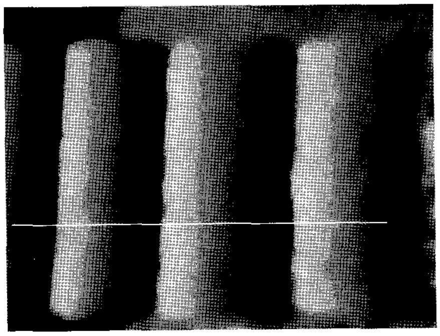


Fig. 14 Wrapped phase processed with median filtering algorithm

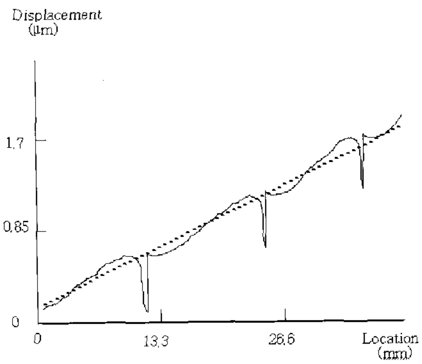


Fig. 15. In-plane displacement of specimen

5. Conclusion

Speckle interferometry with phase-shifting method has been applied to measurement of micro-scale displacement through optical signal processing because it is convenient to measure and gives accurate results. In this paper, 4-step phase-shifting method by PZT is applied to speckle interferometry in order to measure out-of-plane displacement in a spot-welded cantilever. From the optical experiment, a welded area that is invisible from the surface can be easily detected and a micro-scale out-of-plane displacement in the welded area is measured. Then phase-shifting method using directional Fourier transform implemented with PZT has been applied to measurement of in-plane displacement of a specimen that is a rectangular steel plate with a circular hole at the center. Results of the optical experiment agree well with those of ANSYS analysis for the in-plane displacement of specimen. Also, new phase shifting method using a quarter wave plate has been applied to measurement of in-plane displacement in speckle interferometry. Results of optical experiment show that the quarter wave plate can be used for phase-shifting method that is cheap and easy to use in speckle interferometry.

Acknowledgement

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