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Application of ESPI to Measurement of Out-of-plane Displacement in a Spot Welded Canti-levered Plate

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ABSTRACT

Electronic Speckle Pattern Interferometry (ESPI) has been recently developed and widely used because it has the advantage of being able to measure surface deformations of engineering components and materials in industrial areas without contact. The speckle patterns formed with interference and scattering phenomena can measure not only the out-of-plane but also the in-plane deformations. Digital image equipment processes the information included in the speckle patterns and displays the consequent interferogram on a computer monitor. In this study, the experimental results of a canti-levered plate using ESPI were compared with those obtained from the simple beam theory. The ESPI results of the canti-levered plate, analyzed by 4-step phase shifting method, are close to the theoretical expectation. Similarly, out-of-plane displacements of a spot welded canti-levered plate were also measured by ESPI with 4-step phase shifting technique. The phase map of the spot welded canti-levered plate is quite different from that of the canti-levered plate without spot welding.

Key Words : Electronic Speckle Pattern Interferometry (ESPI), Interferogram, Phase shifting technique, Out-of-plane displacement, Digital Image Process, Fringe Analysis

1. Introduction

Laser speckle interferometry can be used to detect the locations of stress concentration of an object and deformation over a whole area to be measured through the shape information in fringe patterns[1,2]. One of the big advantages of laser speckle interferometry is that it can measure the displacement of the object precisely by a non-contact technique using an optical method. ESPI can obtain interferometric fringes by a subtraction process ($I = |I_{before} - I_{after}|$) of the image data.

Small displacement can be measured from such interferometric fringes corresponding to the order of the laser wavelength.

Several researches about in-plane displacement and vibration properties analyzed by ESPI have been reported and the application of ESPI is increasing[3-5]. In this paper, the out-of-plane displacements of a partially spot welded canti-levered plate and of a normal canti-levered plate are measured and compared by application of 4-step phase shifting method to the analyze fringe patterns in ESPI[6].

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2. Optics of ESPI

2.1 ESPI for measurement of out-of-plane displacement

Fig. 1 shows the arrangement of the ESPI optical system for measuring out-of-plane displacement. The interferometric fringe patterns caused by phase differences between the specimen and the reference plane with a PZT (piezoelectric transducer) must be analyzed because the interferometric fringe patterns contain information about out-of-plane displacement of the specimen. The phase difference is made by an optical path difference. The equation of out-of-plane displacement caused by the optical path difference is as follows:

$$w = \frac{\lambda}{4\pi}\phi \quad (1)$$

In Eq. (1), w is z-directional (out-of-plane) displacement, λ is the wavelength of the laser, and ϕ represents the phase difference between before and after out-of-plane displacement.

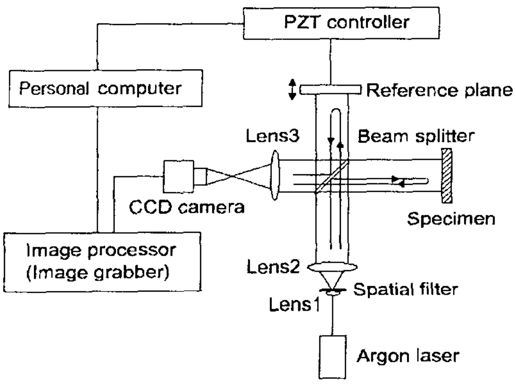


Fig. 1 Arrangement of ESPI optical system for measuring out-of-plane displacement

2.2 4-step phase shifting method in ESPI

The 4-step phase shifting method used in this paper is employed to move the reference plane with the PZT by $\pi/2$ radians in each step and to obtain four fringe patterns with relative phase difference. The phase map is obtained from the four fringe patterns using the arc tangent function. The light intensity of the fringe pattern in ESPI, I_i, is expressed as follows:

$$I_i = I_0\{1 + m(x,y)\cos[\phi(x,y) + \alpha]\} \quad (2)$$

In the above equation, $I_i(x,y)$ is the measured light intensity, I_0 is the average intensity, $m(x,y)$ is the contrast, $\phi(x,y)$ is the phase difference, and α is the initial intensity. The phase map, where the magnitude and sign of displacement can be known, can be obtained as follow.

$$\phi(x,y) = \tan^{-1}\left[\frac{I_4 - I_2}{I_1 - I_3}\right] \quad (3)$$

In Eq. (3), I_1, I_2, I_3 and I_4 are the light intensities at $\alpha = 0$, $\pi/2$, π, $3\pi/2$, respectively. Eq. (3) uses the four fringe patterns with different phases, so that this method is called the 4-step phase shifting method. The phase map obtained by this method has the phase between $-\pi$ radians and $+\pi$ radians due to the property of the arc tangent function. Thus, the phase map has the discontinuous phase at every 2π radians, but this discontinuity can be eliminated by use of the phase unwrapping process and the continuous displacement of the specimen can be obtained[7].

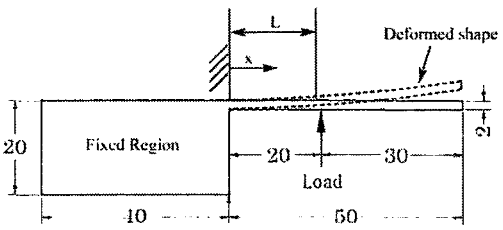
The speckle pattern contains lots of noise and the noise must be filtered out before the phase unwrapping process. The Gaussian blur process in a commercial image processing software package[8] is used to eliminate the speckle noise. An FFT filtering process similar to the Gaussian blur process can be used as well.

3. Experiment

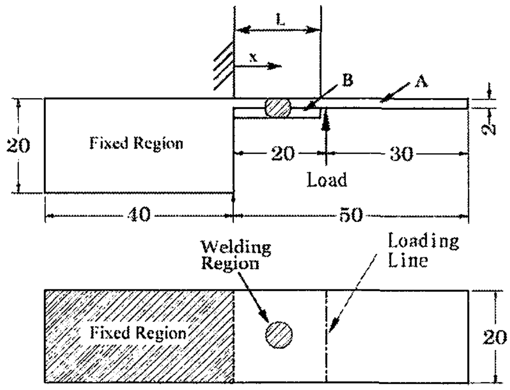
3.1 Specimen and experimental set-up

The specimen used in this experiment is a 2 mm-thick canti-lever made of steel plate. The shape and size of the specimen is shown in Fig. 2. Fig. 2(a) is the normal canti-levered plate that is not spot-welded, and Fig. 2(b) is the canti-levered plate that is spot-welded on the rear side. Its material properties are given in Table 1.

Fig. 3 shows the alignment of the optical components in which the optical set-up for Twyman-Green interferometry is used to measure the out-of-plane displacement. The phase shifting method is used to advance the precision degree of the speckle pattern in the measurement of out-of-displacement, and the phase shifting is performed by the PZT that is controlled with a personal computer.



(a) Normal canti-levered plate (before weld)



(b) Spot welded canti-levered plate (after weld)

Fig. 2 Dimensions of the specimen used for measurement of out-of-plane displacement

Table 1 Physical properties of the specimen[9]

Material	Strength (MPa)		Modulus of Elasticity (GPa)	Poisson's Ratio
	Yield Strength	Ultimate Strength		
Structural Steel	250	450	200	0.3

The expression for the deflection curve for a canti-lever beam subjected to a concentrated load P, as shown in Fig. 2 (a), is

$$\delta = \frac{P}{6EI}(x^3 - 3Lx^2) \tag{4}$$

In Eq. (4), E is the Young's elastic modulus, I is the moment of inertia, L is the distance from the fixed support to the loading point, and x is the distance from the fixed support to any arbitrary point.

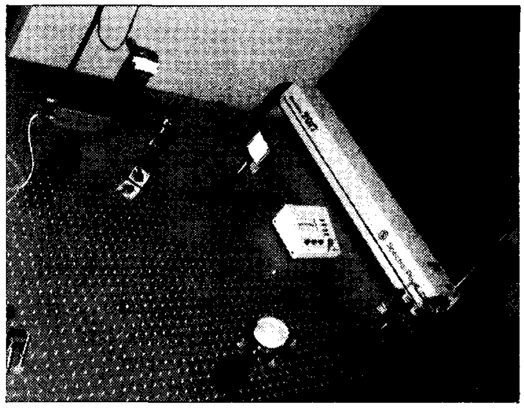
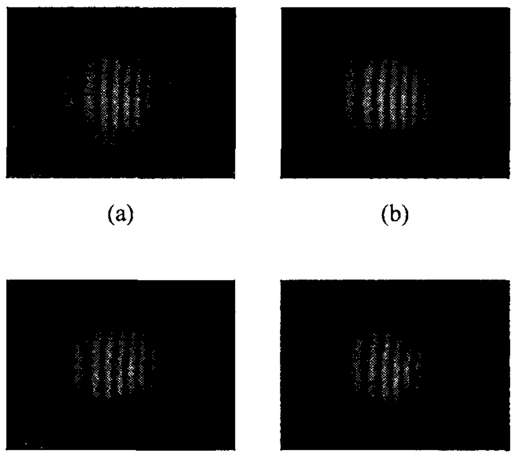


Fig. 3 Optical system for ESPI measurement of out-of-plane displacement

3.2 Results of experiment

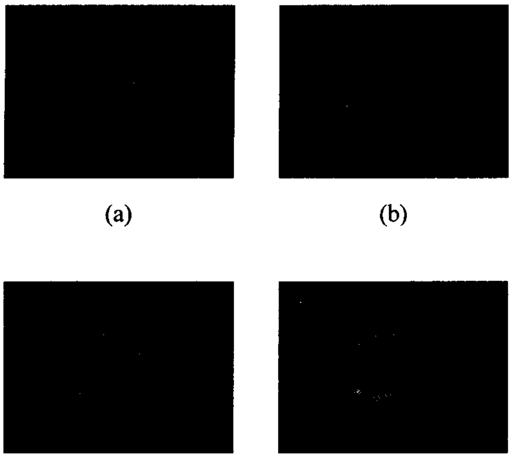
Fig. 4 shows the speckle fringe patterns of a normal canti-lever at difference phases for $\alpha = 0$, $\pi/2$, π, $3\pi/2$. Fig. 5 shows the speckle fringe patterns of a spot welded canti-levered plate at difference phases for $\alpha = 0$, $\pi/2$, π, $3\pi/2$. Those fringe patterns are obtained through a subtraction of before-displacement and after-displacement results of a specimen. The different phases in Figs. 4 and 5 are created by the PZT which controls the phases of fringe pattern by $\alpha = 0$, $\pi/2$, π, $3\pi/2$, as mentioned before.



(a) (b)

(c) (d)

Fig. 4 Speckle fringe patterns of a normal canti-levered plate at difference phases for $\alpha = 0$, $\pi/2$, π, $3\pi/2$



(a) (b)

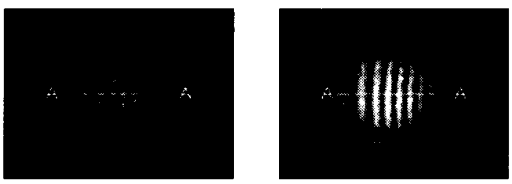
(c) (d)

Fig. 5 Speckle fringe patterns of a spot welded canti-levered plate at difference phases for $\alpha = 0,\ \pi/2,\ \pi,\ 3\pi/2$

As seen in Figs. 4 and 5, the change of fringe patterns is shown near the welded area of the spot welded specimen. To eliminate the noise of the high frequency component in the speckle, the Gaussian blur process is applied to the original image obtained in the experiment. Figs. 6 (a) and (b) are the original image and the Gaussian blurred image, respectively. When the Gaussian blurred image is compared with the original image in Fig. 6, it is clear that the high frequency noise is eliminated.

Fig. 7 shows the light intensities along the line A-A in Fig. 6. There is no doubt that the high frequency noise is eliminated in the Gaussian blurred image.

Fig. 8 is the phase map calculated by Eq. (3) in which four Gaussian blurred images are used. When Figs. 8 (a) and (b) are compared, the phase map of the normal canti-levered plate is uniform, but that of the spot welded canti-levered plate shows a phase reversal at the welded area.



(a) (b)

Fig. 6 (a) Original image and (b) Gaussian blurred image obtained from Fig. 4(a)

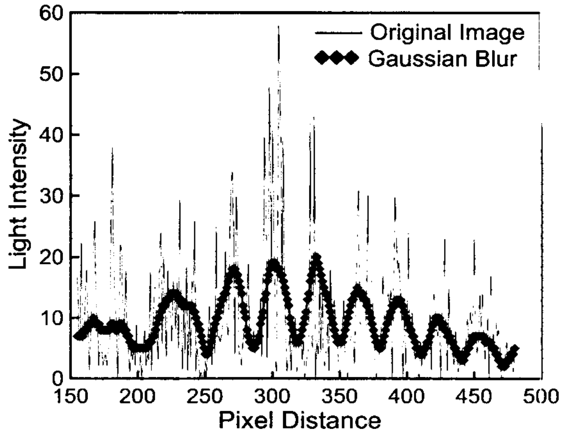
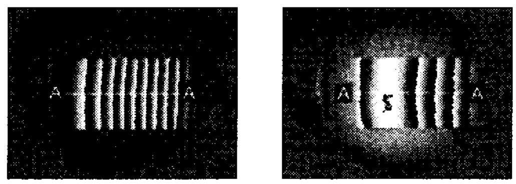


Fig. 7 Comparison of light intensity along line A-A of Fig. 6



(a) (b)

Fig. 8 Wrapped phase images of (a) normal and (b) spot welded canti-lever

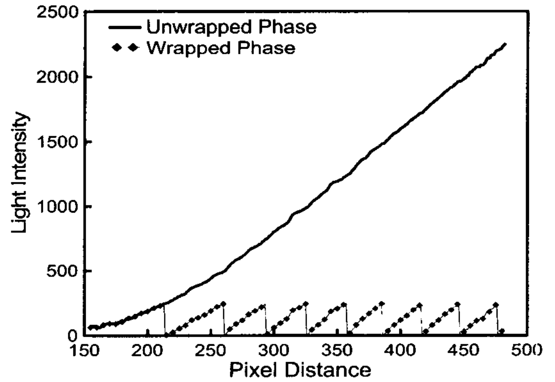


Fig. 9 Wrapped and unwrapped phase distribution along line A-A of Fig. 8 (a)

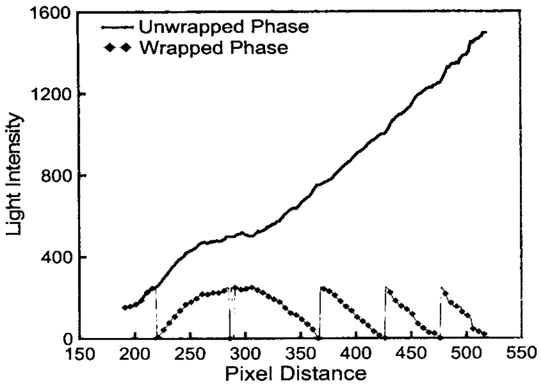
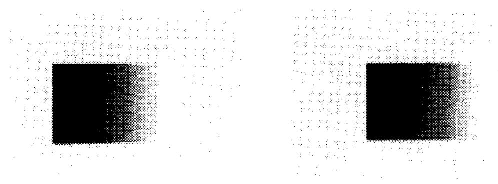


Fig. 10 Wrapped and unwrapped phase distribution along line A-A of Fig. 8 (b)



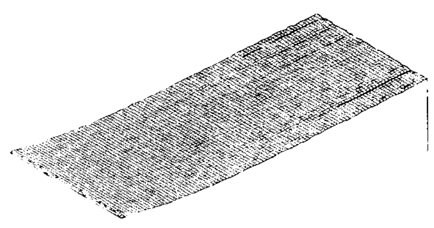
(a) (b)

Fig. 11 Unwrapped phase map of Fig. 8

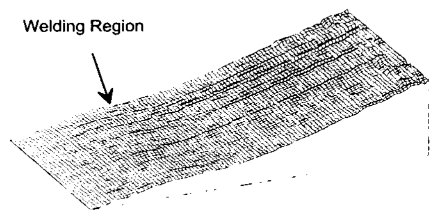
Fig. 9 shows wrapped and unwrapped phase distributions along line A-A of Fig. 8(a) of the normal canti-levered plate. Fig. 10 shows wrapped and unwrapped phase distributions along line A-A of Fig. 8(b) of the spot welded canti-levered plate.

Fig. 11 is the unwrapped phase map of Fig. 8. Fig. 12 is 3-D view of the unwrapped phase image of Fig. 11. It is clearly seen in Figs. 12 (a) and (b) that continuous displacement occurred in the normal canti-levered plate but the displacement at the spot welded area was hump-shaped in the spot welded canti-levered plate.

Fig. 13(a) shows the displacement distribution obtained from the theory and from the phase shifting method along line A-A of Fig. 8. It shows that the result of ESPI is almost the same as that of the theoretical calculation for the normal canti-levered plate which is not spot welded. The maximum error of 0.076 μm occurs at approximately 7.9 mm from the fixed area of the canti-levered plate. However, in general, the measured displacement by the ESPI



(a) normal canti-lever

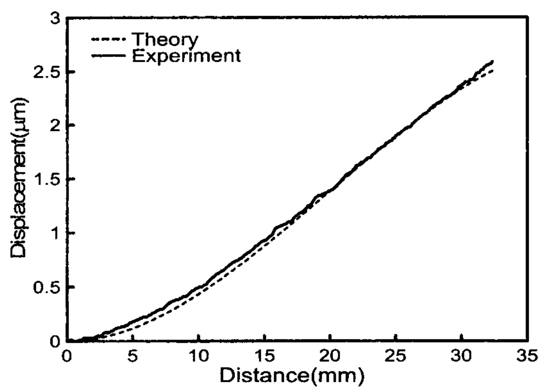


(b) spot welded canti-lever

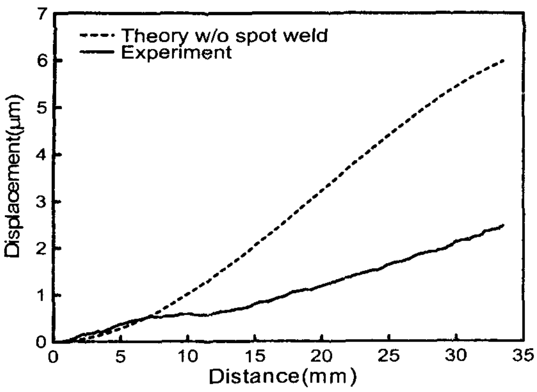
Fig. 12 3-D view of unwrapped phase image of (a) Fig. 11(a) and (b) Fig. 11(b)

experiment is quite close to the theoretically expected displacement. Thus, it is proved that the physical out-of-plane displacement can be directly measured by the ESPI method.

Fig. 13(b) shows the displacement distribution obtained from the spot welded canti-levered plate. The displacements, 0.582 μm, 1.183 μm, 2.134 μm, are measured at 10 mm, 20 mm, 30 mm from the fixed area of the spot welded canti-levered plate, respectively.



(a) normal canti-lever



(b) spot welded canti-lever

Fig. 13 Displacement distribution obtained from theory and from the phase shifting method along line A-A of Fig. 8

As a reference, the other displacements, 1.006 μm, 3.219 μm, 5.432 μm, are estimated at 10mm, 20mm, 30mm from the fixed area of the normal canti-levered plate. Therefore, the displacement for the same load can decrease if the canti-levered plate is reinforced by spot-welding, and the spot welded area that is not visible can be easily detected by use of speckle interferometry.

4. Conclusions and Discussions

The 4-step phase shifting method applied to an ESPI experiment has been used for the measurement of out-of-plane displacement in the normal canti-levered plate and the spot welded canti-levered plate. The measured displacement of the normal canti-levered plate agreed to the theoretical value within 0.076 μm.

That is, it is proved that the physical out-of-plane displacement can be directly measured and precise measurement with a nanometer resolution is possible. Also, a welded area that is invisible from the surface can be detected and a small out-of-plane displacement in the welded area can be measured.

The distribution of displacement shows a slight non-linearity in the period of fringe, and therefore, further work is necessary for more precise measurement. Also, noise due to speckle has to be eliminated before the phase shifting method is applied. The Gaussian blur process similar to FFT filtering is used to eliminate the noise in this work.

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