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Analysis of an Inside Crack of Pressure Pipeline Using ESPI and Shearography

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Abstract In this study, shearogrpahy and ESPI have been used for quantitative analysis of an inside crack of pipeline and both of them appeared suitable to qualitatively detect inside crack. However, shearography needs several effective factors including the amount of shearing, shearing direction and induced load for the quantitative evaluation of the inside crack. In this study, the factors were optimized for the quantitative analysis and the size of cracks has been determined. Although the effective factors in shearography has been optimized, it is difficult to determine the factors exactly because they are related to the details of cracks. On the other hand, ESPI is independent on the details of a crack and only the induced load plays an important role. The out-of-plane displacement was measured under the optimized load and the measured were numerically differentiated, which resulted in an equivalent to the shearogram. The size of cracks can be determined quantitatively without any detail of a crack.

Keywords: electronic speckle pattern interferometry (ESPI), shearography, quantitative analysis

1. Introduction

Speckle interferometry allows us to measure a surface displacement and the dynamic displacement of an object. Since Butters and Leendertz introduced CCD camera and filtering techniques into speckle interferometry, a fringe pattern contouring the surface displacement or the dynamic displacement can be obtained in quasi-real time, non-contact and as a whole field (Jones and Wykes, 1983). The methods are known as electronic speckle pattern interferometry (ESPI) and shearography and have been further developed by using the analog and the digital signal processing techniques by several authors. Shearography is used more generally for non-destructive inspection. It is less susceptible to environmental and mechanical noise than ESPI because the spatial derivatives of a surface displacement are directly measured and also the method allows a simple interferometer (Ettemeyer, 1996; Toh, Chau and Sim, 1997). On the other hand, ESPI can measure the in-plane and the out-of-plane surface displacements. Hung(1997) also indicated that shearography is more practical than ESPI for nondestructive inspection after comparing ESPI with shearography. Although shearography has many advantages for qualitative evaluation, so many effective factors including the amount of shearing, shearing direction and induced load exist as barrier for the quantitative analysis of inside defects. Since the factors are highly dependent on inspectors skill and also affect the in-situ workability. In this study, the effective factors in shearography were optimized for quantitative analysis and the size of

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inside crack has been determined. However, even if these factors in shearography were optimized, we found that it would be very difficult to determine these factors exactly because they are related to the details of cracks. On the other hand, ESPI is independent of the details of a crack and only the induced load plays an important role. In order to evaluate a crack at the inner surface quantitatively, the out-of-plane displacement was measured by ESPI and the displacement was differentiated with a simple numerical processing, which is an equivalent to the result of shearography. Consequently, the size of cracks can be determined quantitatively without the details of a crack.

2. Background

2.1. Electronic Speckle Pattern Interferometry (ESPI)

Holographic interferometry has been a powerful technique in the measurement of surface displacement. A hologram has fringe patterns that represent the relative displacement of an object surface when the object is loaded. However, the process of analysis is very complicated. Several speckle interferometry techniques have been developed in which the recording and reconstruction processing is fairly simple (Cloud, 1995). ESPI is one of the methods. The ESPI fringe pattern represents both the in-plane aand the out-of-plane displacement. In this study, the interferometer sensitive to the out-of-plane displacement has been used as shown Fig. 1 and the surface displacement of an object was measured and evaluated by using the 4-step phase shifting and unwrapping method.

2.2. Shearography

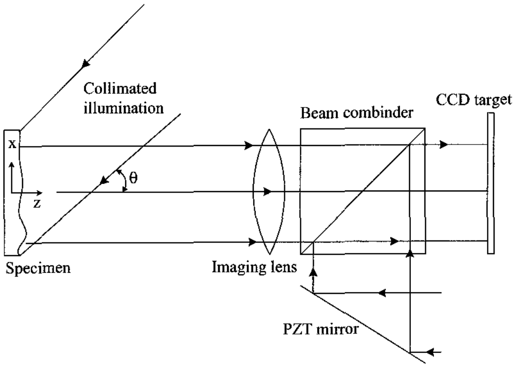


Fig. 1 A basic arrangement of the ESPI sensitive to the out-of-plane displacement

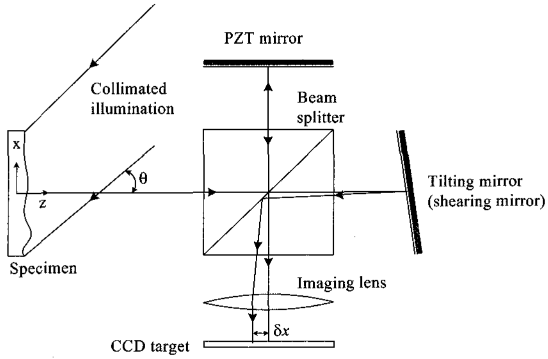
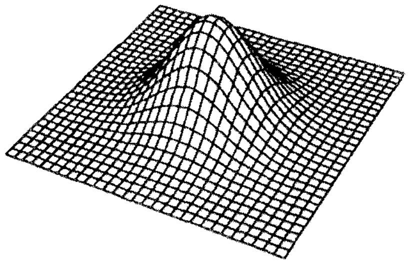


Fig. 2 A basic arrangement of the speckle pattern shearing interferometer

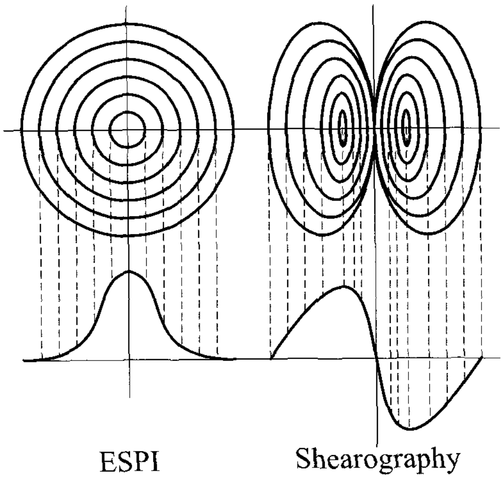
Shearography measures the first derivative of static surface displacements, of which the interferometer is shown in Fig. 2. The object is viewed through the Twyman-Green interferometer arrangement by CCD camera. The PZT mirror for phase shifting technique lies parallel to the CCD camera and one can shift the images with respect to parallel image by slightly tilting mirror. The direction and the amount of the tilt (shearing) can be manually adjusted. The intensity at a point on the image plane corresponds to the superposition of the light scattered from two adjacent points on the original object. When the object is deformed, an arbitrary point (x, y) on the object surface is displaced to $(x+u, y+v, w)$, where u, v, w are the displacement components of x-, y- and z-axis, respectively. And a neighboring point $(x+\delta x,\ y)$ is displaced to $(x+\delta x+u+\delta u,\ y+v+\delta v,\ w+\delta w)$. Deformation of the object induces a phase difference between two neighboring points. In the optical set-up, the expression for the relative phase difference is given by eqn. (1) (Rastogi, 2001).

$$\Delta\phi(x,y)=\frac{2\pi}{\lambda}\left[(1+\cos\theta)\frac{\partial w}{\partial x}(x,y)+\sin\theta\frac{\partial u}{\partial x}(x,y)\right]\delta x \qquad \cdots\cdots\cdots\cdots(1)$$

where $\triangle\phi$ is the relative phase change between before and after the deformation, λ is the wavelength of light source, θ is the angle between illumination and the surface normal, $\partial w/\partial x$ and $\partial u/\partial x$ are the first-order partial derivative of the out-of-plane and the in-plane displacements of the deformed object, respectively, and δx is the amount of shearing between the speckle patterns. Fig. 3 shows the relationship of the two methods. Shearography can be related with the first derivative of ESPI due to the difference of interferometers. ESPI can measure the out-of-plane displacement and shearography directly measures the first derivative of the displacement. The size of crack is determined by measuring the peak-to-peak of the line profile in sherography. The length between two peaks is varied due to the change in the effective factors.



(a) Real deformation of an object surfa



(b) Comparison of the line profiles

Fig. 3 Relationship between ESPI and shearography

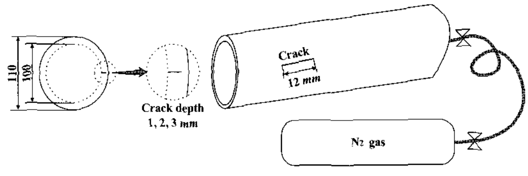


Fig. 4 Pipeline system

3. Experiment

A pressurized pipeline system with artificial inside cracks was designed, which consists of a pipe, pressure valves and pressurizing system as shown in Fig. 3. The artificial cracks were parallel to pipe axis with 12 mm in length and 1, 2, and 3 mm in depth from the inner surface of the pipeline. Material was a stainless steel generally used for the pipeline with allowable pressure of 20 MPa. The pipeline to be inspected was loaded with inner pressure change. The pipeline would deform only by a few micrometers. In the areas with a weakened wall caused by crack or corrosion, the wall of the pipeline was deformed more by the inner pressure change than in the areas with no defect. The difference between a loaded and an unloaded state provided the information about the surface displacement of the pipeline. The displacement gradient was obtained by deriving the line profile in the axis of the pipeline with shearography. The surface displacement was obtained directly by ESPI. An image of the unloaded pipeline was recorded and stored as a reference image by an image processor. All the following images of the loaded pipeline were subtracted from the reference image in image processor in real time and the result was displayed in a video monitor. In order to evaluate the size of a crack quantitatively, phase shifting and unwrapping method has been used; where the 4 phase-shifted speckle interferograms are generated by PZT. The relative phase could be calculated from the 4 speckle interferograms ($I(1) \sim I(4)$) using eqn. (2). The result was also displayed on a video monitor (Andra, Mieth and Osten, 1991).

$$\Delta\phi = \tan^{-1}\left[\frac{I(3)-I(1)}{I(4)-I(2)}\right] \qquad \text{......(2)}$$

where,

$$I(1) = I_R + I_O + 2\sqrt{I_R I_O}\cos\Delta\phi$$
$$I(2) = I_R + I_O + 2\sqrt{I_R I_O}\cos(\Delta\phi + \pi/2) = I_R + I_O - 2\sqrt{I_R I_O}\sin\Delta\phi$$
$$I(3) = I_R + I_O + 2\sqrt{I_R I_O}\cos(\Delta\phi + \pi) = I_R + I_O - 2\sqrt{I_R I_O}\cos\Delta\phi$$
$$I(4) = I_R + I_O + 2\sqrt{I_R I_O}\cos(\Delta\phi + 3\pi/2) = I_R + I_O + 2\sqrt{I_R I_O}\sin\Delta\phi$$

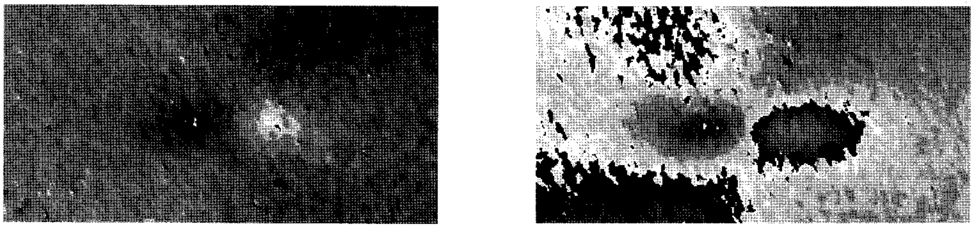
I_R: the reference beam irradiance

I_O: the object beam irradiance

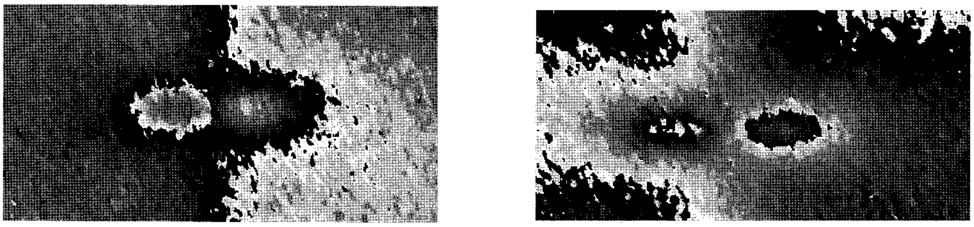
4. Results

4.1. Quantitative Analysis by Shearography

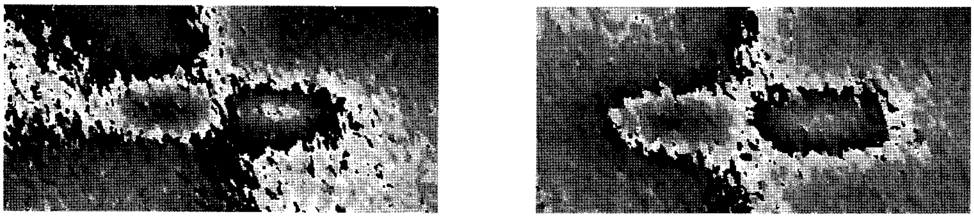
Fig. 5 shows shearography fringe patterns with the change of the amount of shearing (δx). The more the shearing distance is increased, the more the center of two ellipses is moving far away, which can be related to the size of cracks. Fig. 6(a) shows the relationship between the estimated crack size and the amount of shearing. The crack size can be determined by measuring the peak-to-peak of the line profile obtained by shearography. The size of crack is given as 12mm in length. From the results, in the case that the amount of shearing was within crack size, the size of crack was evaluated very well. In the case that the amount of shearing



(a) 5 mm (b) 10 mm

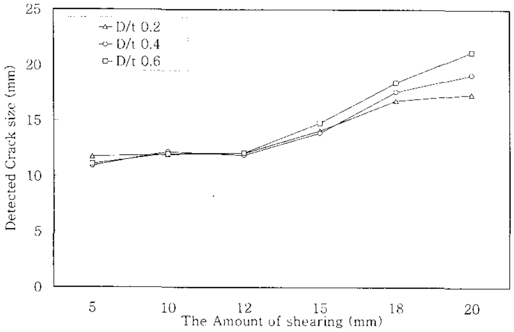


(c) 12 mm (d) 15 mm

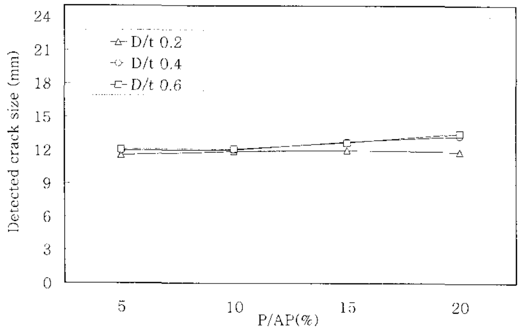


(e) 18 mm (f) 20 mm

Fig. 5 Shearography fringe patterns with the amount of shearing is beyond the crack size, the size of crack was much overestimated. The results showed that the amount of shearing should be an important effective factor and the size of crack could be determined exactly only when it was within the crack size. In addition, the depth of crack could not be evaluated with the surface information only and it appeared not to be related to the amount of shearing. Fig. 6(b) shows the relationship between the estimated crack size and the normalized pressure, which is the induced pressure divided by the allowable pressure of the pipeline. Although the induced load was increased, the crack size was determined with a relatively small error. It showed a optimal result when the pressure is within 10% of the allowable pressure. The induced pressure has influenced the determination of crack size but the influence was so little and also the shearing direction must be paralleled to crack direction. If the crack had circular shape, the crack size would be constant at all shearing directions and the shape of a crack could be estimated by changing the direction of shearing. Although the effective factors were optimized, we found that the factors could be related to the size and shape of cracks. If the unknown crack were inspected, it would be difficult to optimize the factors.

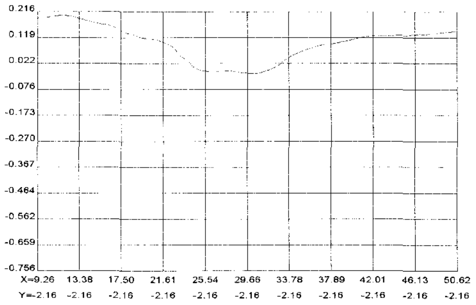


(a) The amount of shearing vs. Crack size

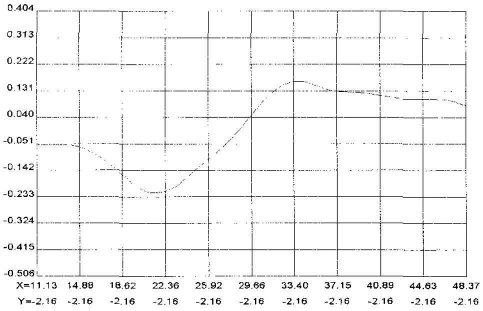


(b) Normalized pressure vs. Crack size

Fig. 6 Evaluation of thecrack size due to the change of the effective factors (t: Wall thickness, D: Crack depth, P: Induced pressure, AP: Allowable pressure)



(a) Line profile of surface displaceme



(b) The first derivative of (a)

Fig. 7 Line profile of the object surface around a crack by ESPI

4.2. Quantitative Analysis by ESPI

Although searography is less susceptible to environmental and mechanical noise, the effective factors related to the details of crack exist as obstacles for the quantitative evaluation. Therefore, ESPI has been employed for the determination of crack size. Sheargoraphy can be related with the first derivative of ESPI. The out-of-plane surface displacement was measured by ESPI and the displacement was differentiated numerically. The results were the spatial derivatives of out-of-plane displacement, which can be an equivalent to those of shearogrpahy. On the other hand, ESPI needs no adjustment over any optical component for the determination of crack size and only the induced load have an effect on quantitative evaluation. The load optimized as 10 % of the allowable pressure was induced and the surface displacement was measured and differentiated. Fig. 7(a) shows the line profile of surface displacement by ESPI when the surface was caved in. Fig. 7(b) is the first derivative of surface displacement. The crack size from the result was determined by measuring the peak-to-peak length. The crack was evaluated as 12 mm in length, which is well agreed with the artificial crack size within 3 %.

5. Conclusions

In this study, shearogrpahy and ESPI were used for quantitative analysis of a inside crack of pipeline and both of them appeared suitable to qualitatively detect inside crack. However, shearography needs several factors including the amount of shearing, shearing direction and induced load for the determination of the crack size. In this study, the effective factors were optimized for the quantitative analysis. When crack size was equal to the amount of shearing, the size of cracks was determined accurately and was closely related with shearing direction. In the inspection of an unknown defect, however, it would be difficult to determine two factors exactly because the factors are related to the details of a crack. On the other hand, ESPI appeared to be independent of the details of a crack and only the induced load plays an important role. The out-of-plane displacement was measured under the optimized load and was numerically differentiated, with resulting in an equivalent to a shearogram. The size of cracks can be determined quantitatively without any details of a crack. In the field applications, shearography could inspect an object qualitatively to detect any crack first, then ESPI can measure the surface displacements around the crack for the quantitative evaluation.

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