DEVELOPMENT OF A SELF REFERENCE LOCK-IN THERMOGRAPHY AND ITS APPLICATION TO REMOTE MONITORING OF FATIGUE CRACKS IN STEEL STRUCTURE

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Abstract

Thermoelastic stress measurement has been getting an increasing attention as a non-destructive evaluation technique for fatigue crack in steel structures. In the thermoelastic stress measurement, stress distribution is measured by lock-in infrared thermography, which correlates temperature change due to the thermoelastic effect with reference-load signal. Load signal from external source, such as load-cell, strain gage or displacement gage, is usually employed as a reference signal in the conventional lock-in technique. In this study, a self-reference lock-in infrared thermography was newly developed, in which a reference signal was constructed by using the same sequential data on thermoelastic temperature change. It enabled us to measure the distribution of relative intensity of applied stress under random loading without using any external load signal. Proposed self-reference lock-in thermography was applied for crack identification based on the detection of the singular stress field in the vicinity of crack tips. Experimental investigations were conducted using welded steel samples. It was found that significant temperature change was observed at the crack tips, demonstrating the feasibility of the proposed technique.

1. Introduction

In recent years, crack propagations in aged structures have become a serious problem which was lead to catastrophic failures of the structures. In large-scale steel structures for critical usage, such as highway bridges or cranes, non-destructive inspection for possible deterioration and damages are necessary in order to ensure safety and to estimate the remaining life of these structures.

Thermoelastic stress analysis (TSA) has been getting an increasing attention as one of the effective NDE techniques for crack identification in steel structures. TSA is a full-field, non-contacting technique for surface stress mapping of structures based on the thermoelastic effect. When measurement is performed for a cracked structure, it is possible to obtain information about stress distribution. Crack can be detected from a singular stress field due to the crack, since significant stress concentration is observed in the vicinity of a crack tip. Thus, visualization of a singular temperature distribution induced by singular stress field enables crack detection [1].

Since thermoelastic temperature change is quite small, lock-in infrared thermography using reference-load signal synchronized with stress, is commonly employed to improve the precision of stress measurements. A load signal from an external source, such as load-cell, strain gage or displacement gage, is usually employed as a reference signal in the conventional technique. However, it is usually difficult to obtain a reference-load signal from actual large-scale steel structures in service. Further the observed load signal is not a clear sinusoidal wave because it contains the characteristic oscillation components in service. These facts show that the conventional lock-in infrared thermography is not applicable.

The present authors [2] proposed a self-reference lock-in infrared thermography technique, which does not require an external reference signal and can be employed even under random loading. In this paper, several results of preliminary experimental studies of fatigue crack detection are shown.

2. Self-Reference Lock-in Thermography

2.1. Thermoelastic Stress Measurement

If adiabatic and elastic conditions are achieved, the temperature variations are proportional to the sum of principal stresses. The relation between the principal stresses and the temperature changes due to the application of a cyclic load is expressed by the following equation.

$$\Delta T = \frac{-aT\Delta(s_1 + s_2)}{rC_p} \quad (1)$$

Here σ_1 and s_2 are the principal stresses, a is the coefficient of thermal expansion, T is the absolute temperature of the material, r is the density and C_p is the specific heat at constant pressure.

2.2. Generation of Reference Signal

An infrared image of a welded plate specimen subjected to sinusoidal cyclic load is shown in Fig. 1(a). Fillets were welded on the specimen and the stress concentration occurs near the welded region. A fatigue crack is propagating in this region. Significant temperature change is observed due to the singular stress field in the vicinity of the crack tips. However it is not detectable in raw images of infrared thermography. Lock-in technique is required for visualizing the thermoelastic temperature change.

An infrared signal obtained from the region "A" that is located in the vicinity of the crack tip is shown in Fig. 1(b) with a solid line. In Fig. 1(b), only variable component is extracted and plotted; i.e. the mean value is subtracted from the original signal. At the same time, an infrared signal obtained from region "B" that is located in a remote region, where a uniform stress is applied, is shown with a broken line. As is seen in Fig. 1(b) the temperature changes obtained from the region "A" and "B" are in-phase and have the similar waveform but big differences are found in their amplitudes. Consequently if a reference signal is constructed from the signal obtained from region "B", it is possible to perform correlation processing without an external reference signal.

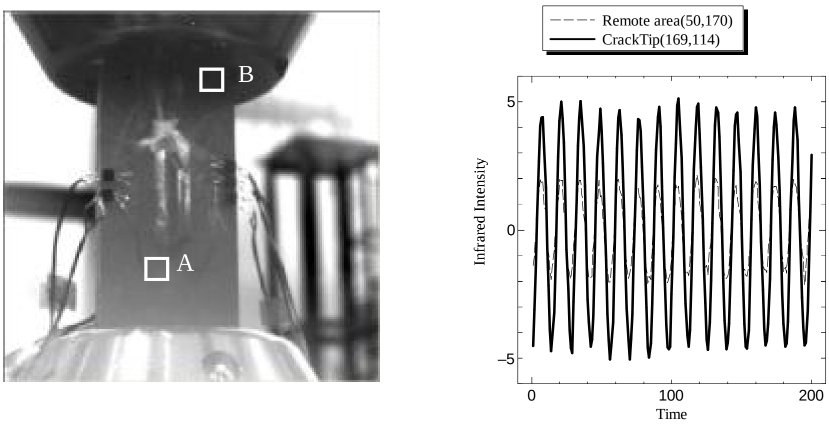
2.3. Lock-in Process under Random Loading

The relative magnitude of infrared signal induced by random load can be determined through the least squares approach. This methodology was developed by Lesniak et al. [3]

Assume that a body is subjected to a random load whose waveform is expressed as f. The infrared signal obtained from region "A" can be approximated as follows.

$$Y_n = A + Bf_n \quad (2)$$

Where A is the DC offset, B is an influence coefficient of the reference, n is the frame number and N is a total frame number. To calculate the influence coefficient, the square sum of deviations between approximate expression and infrared signal obtained from the region "A"



(a) Infrared image of welded specimen *(b) Thermoelastic temperature change*

Figure 1*: Thermoelastic temperature change obtained for welded plate specimen*

defined as follow is minimized.

$$\Delta^2 = \sum_{n=1}^{N} (y_n - Y_n)^2 \qquad (3)$$

Here y is the thermal signal obtained from region "A". B is obtained by the following equation.

$$B = \frac{\begin{vmatrix} N & \Sigma y_n \\ \Sigma f_n & \Sigma y_n f_n \end{vmatrix}}{\begin{vmatrix} N & \Sigma f_n \\ \Sigma f_n & \Sigma (f_n)^2 \end{vmatrix}} = \frac{N\Sigma y_n f_n - \Sigma y_n \Sigma f_n}{N\Sigma (f_n)^2 - (\Sigma f_n)^2} \qquad (4)$$

It is possible to obtain the correlation between the fluctuations of infrared signal in remote region and any other region, when this calculation is performed on all the pixels. Values of B indicate a relative intensity of thermoelastic temperature change, i.e. against that of remote stress area.

2.4. Advantages

The advantages of the self-reference lock-in thermography are described below. This method does not require any external reference signal. The proposed technique can be applied under random loading. The values obtained indicate relative intensity of applied stress and is effectively employed for stress concentration area due to notches or cracks.

3. Experimental Investigation for Welded Plate Specimen

3.1. Welded plate specimen

The crack detection by the self-reference lock-in thermography was performed for welded specimens as shown in Fig. 2. Two ribs were fillet welded to each side of a steel plate with 450 mm in length, 100 mm in width and 14 mm in thickness. The base metal and weld metal of specimens were JIS-SM490B and MG55 (Kobe Steel, Ltd.), respectively. The specimens were coated with structural anticorrosive paint to realize similar condition as actual structures. Further, specimens are painted with flat-black paint to avoid reflection and to increase the emissivity.

In order to make a fatigue crack initiate and propagate, cyclic load was applied to the specimen using a servo-hydraulic testing machine. Loading frequency was 10 Hz, and stress amplitude was 100 MPa. The temperature change was measured using IR focal plane array cameras with indium antimonide array detector.

3.2. Experimental results

The experimental results obtained by the self-reference lock-in thermography were compared with those by the conventional lock-in technique using an external reference signal. To obtain the results at the same time, two infrared cameras were simultaneously used. Figure 3(a) shows the result obtained by the conventional lock-in technique and Fig. 3(b) shows that obtained by the proposed self-reference lock-in technique. It is found that the result obtained by the self-reference lock-in technique is in good agreement with that obtained by the conventional lock-in technique regarding the location and the shape of the stress concentration field in the vicinity of the crack. The compressive stress field near the center of the crack is also observed as the temperature change with negative phase against the reference signal. Good agreement can be found again between two techniques on the shape of the compressive stress filed.

Figure 4 shows a process of crack propagation under cyclic load at the stress amplitude of 100MPa and the load frequency of 10Hz. When a crack was relatively small as in Figs. 4(a) and (b), the singular stress field in the vicinity of the crack tips was not clearly detected. On the other hand, compressive stress near the center of the crack was detected. At the stage where the crack has grown enough as in Figs. 4(c) and (d), the

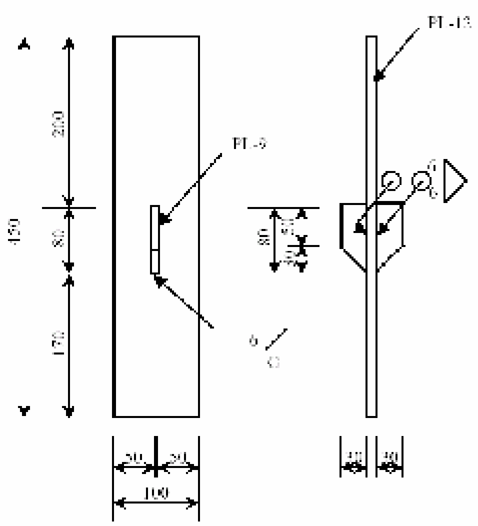
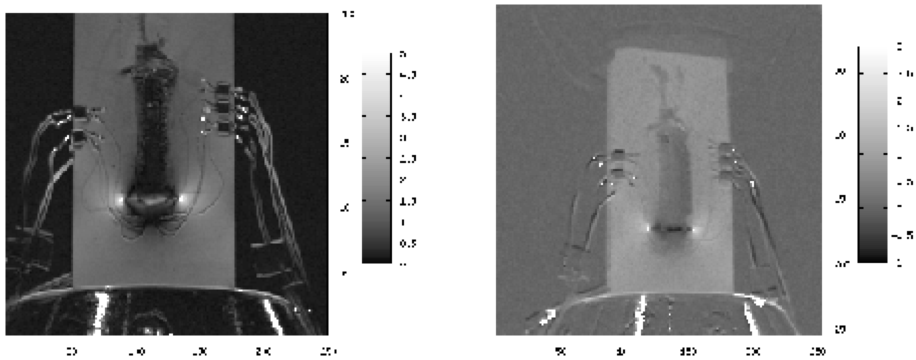
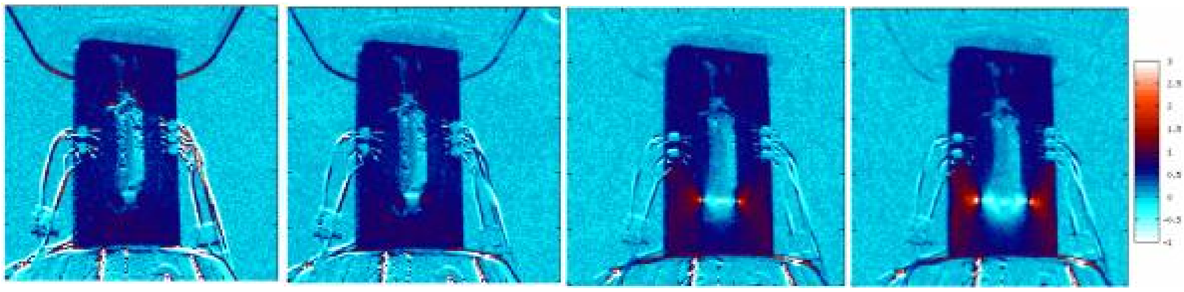


Figure 2: *Dimensions of welded plate specimen.*



(a) Conventional Technique *(b) Self-reference lock-in technique*

Figure 3*: Comparison of lock-in mesurement between conventional lock-in and proposed lock-in techniques.*



(a) 1,100,000 cycles *(b) 1,200,000 cycles* *(c) 1,400,000 cycles* *(d) 1,420,000 cycles*

Figure 4*: Results of self lock-in measurement for crack detection in crack propagation test.*

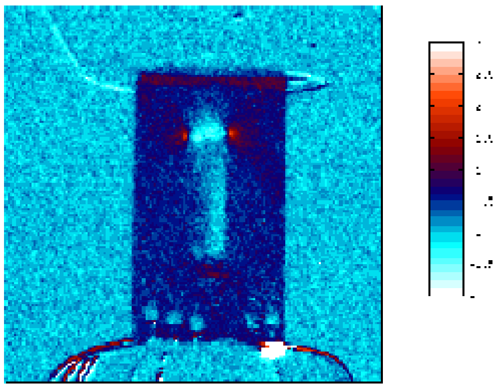


Figure 5*: Results of crack detection using telescopic lens.*

singular stress field in the vicinity of the crack tips is clearly observed. This singular stress field becomes clearer with crack growth; i.e. larger temperature change is observed in Fig. 4(d) than in Fig. 4(c).

The self-reference lock-in technique allows us to perform the crack detection from a distance by using a telescopic lens. This is very useful for actual nondestructive testing of structures in service. The telescopic lens employed in this experiment has a focal length of 250mm. The distance from the lens to the specimen was about 9.8m. The result is shown in Fig. 5. It should be noted that the specimen used in this measurement is not the same as one illustrated in Fig. 4: in this specimen a fatigue crack was initiated and propagated in the opposite part of the fillet. In Fig. 5, the singular stress field is observed in the vicinity of the crack tips and the crack is detected. It is noteworthy that the crack could be detected in spite of degradation due to infrared attenuation by optical system of telescopic lens.

4. Experimental Investigation for Steel Structure Specimen

The crack detection by the self-reference lock-in technique was performed for a steel specimen, which simulates an actual highway bridge using H-shaped steel members as shown in Fig. 6. The scale of this specimen is the same as the member of actual structures such as highway box girder. The specimen has 4,000mm in length, 400mm in width and 625mm in height. The specimen is made of JIS-SS400 steel plate with thickness of 8mm. Three point bending test was conducted for the specimen in order to make the fatigue crack initiate and propagate. Loading frequency was 5Hz, and the loading amplitude was 59kN. The loading waveform was sinusoidal. The measurement region was painted with flat black

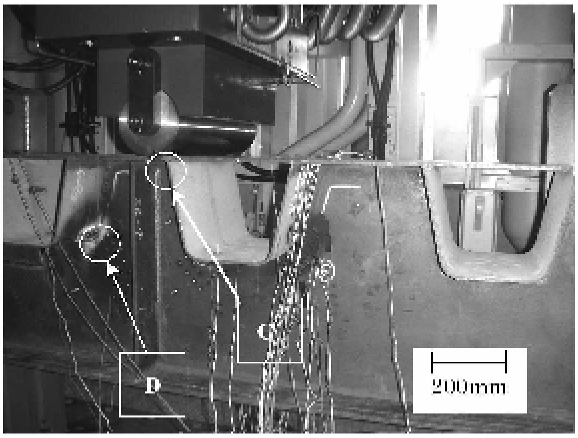
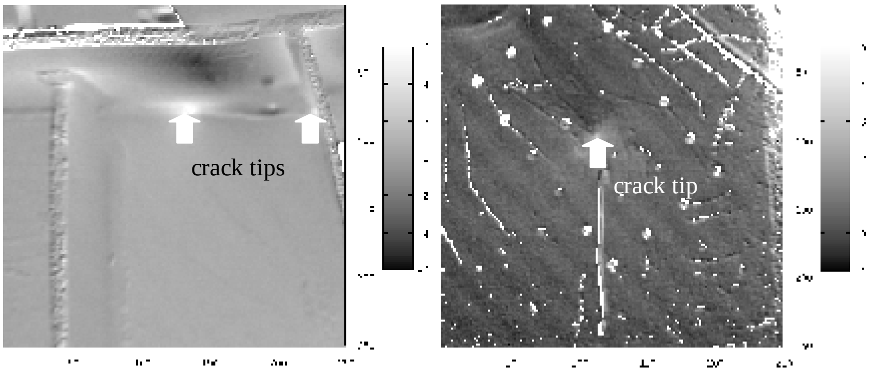


Figure 6*: Photograph of beam specimen made of a steel specimen which simulates an actual highway bridge using H-shaped steel members*



(a) Region "C" *(b) Region "D"*

Figure 7*: Results of crack detection in steel structure specimen.*

paint to avoid reflection and to increase emissivity.

A crack is detected in the region "C" and "D" in Fig. 6. There was a central crack in region "C" and an edge crack in region "D". Figure 7 shows the result obtained by the self-reference lock-in technique. The arrows in Fig. 7 indicate the singular stress field in the vicinity of the crack tips. It is found that the singular stress field in the vicinity of the crack tips is clearly detected.

5. Conclusions

In this study, a self-reference lock-in infrared thermography was newly developed, in which a reference signal was constructed by using the same sequential data on thermoelastic temperature change. Developed self-reference lock-in thermography was applied for crack identification based on the detection of the singular stress field in the vicinity of crack tips. Experimental investigations were conducted using welded steel samples. It was found that significant temperature change was observed at the crack tip, demonstrating the feasibility of the proposed technique.

6. Acknowledgement

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7. References

[1] Sakagami, T., Kubo, S., Fujinami, Y. and Kojima, Y., "Experimental Stress Separation Technique Using Thermo-elasticity and Photoelasticity and Its Application to Fracture Mechanics", *JSME International Journal, Series A*, Vol.47, No. 3, 298-304, 2004.

[2] Sakagami, T., Nishimura, T., Kubo, S., Sakino, Y. and Ishino K., "Development of a Self-reference Lock-in Thermography for Remote Nondestructive Testing of Fatigue Crack (1st Report: Fundamental Study Using Welded Steel Samples)", *Transactions of the Japan Society of Mechanical Engineers, Series A*, 2006 (in-press).

[3] Lesniak, J., Boyce, B., Howenwater, G., "Thermoelastic Measurement Under Random Loading", *Proc. of the SEM Spring Conf.*, Soc. for Exp. Mech., 504-507, 1998.