Development of self-reference lock-in thermography and its application to remote nondestructive inspection of fatigue cracks in steel bridges

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Abstract

A new remote nondestructive evaluation technique, based on thermoelastic temperature measurement by the infrared thermography, was developed for evaluation of fatigue cracks propagated from welded joints in steel bridges. Fatigue cracks were detected from localized thermoelastic temperature change at crack tips due to stress singularity under wheel loading from traffics on the bridge. Self-reference lock-in data processing technique was developed for the improvement of signal-to-noise ratio of the thermal images obtained in the crack detection process. In this paper, experimental results of fatigue crack detection by the self-reference lock-in thermography are reviewed.

1. Introduction

Recently, crack propagation in aged structures has become a serious problem which leads to catastrophic failure of the structures. In large scale steel structures for critical usage, such as highway bridges, non-destructive inspection for deteriorations and damages are necessary in order to ensure safety and to estimate the remaining life of these structures.

As conventional nondestructive testing (NDT) techniques for steel bridges, visual testing, magnetic particle testing and ultrasonic testing have been commonly employed. However, these NDT techniques were time- and labor-consuming techniques, because special equipments for inspection, such as a scaffold or a tower wagon, were required. Further these conventional NDT techniques can be simply employed for crack detection, but it is impossible to directly measure physical quantities for evaluating the remaining strength based on the fracture mechanics.

In these circumstances, thermoelastic stress analysis (TSA) by the infrared thermography has been getting an increasing attention as a non-destructive testing and evaluation method for fatigue cracks in steel structures. When the TSA measurement is performed for a cracked structure, cracks can be detected from singular stress fields due to the cracks, since significant thermoelastic temperature changes can be observed due to stress concentrations around crack tips. Thus this technique can be employed for the detection of fatigue cracks propagated from welded joints in steel bridges. Steel bridges being concerned with fatigue crack propagations are always subjected to frequent and heavy wheel loadings from traffics on the bridge. Therefore if the infrared thermography is employed for the continuous temperature monitoring around fatigue cracks, fatigue cracks can be identified from localized thermoelastic temperature change due to stress singularity at crack tips under variable wheel loadings.

Since thermoelastic temperature change is very small, lock-in infrared thermography using reference 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 TSA technique. However, it is difficult to obtain a reference signal from actual steel bridges in service. Furthermore the observed load signal does not have a clear sinusoidal waveform, because it contains the random waveform components due to the in-service wheel loading by the vehicles. These facts show that the conventional lock-in infrared thermography is not applicable for TSA in steel bridges.

The present authors developed a self-reference lock-in thermography [1], which does not require any external reference signals and can be employed even under random loading. Nondestructive inspections of fatigue cracks in steel bridges were conducted by the proposed self-reference lock-in thermography in the previous paper [2]. In this paper, experimental results of fatigue crack detection by the self-reference lock-in thermography are reviewed.

2. Thermoelastic Stress Analysis

Dynamic stress change causes very small temperature change under the adiabatic condition in solid. This phenomenon is called as thermoelastic effect and is described by the following Lord Kelvin’s equation that relates temperature change (ΔT) to a change in the sum of the principal stresses (Δσ) under the cyclic variable loading.
\[ \Delta T = -\frac{\alpha}{\rho C_p} T \Delta \sigma \]  
(1)

\( \alpha \) : Coefficient of thermal expansion  
\( \rho \) : Mass density  
\( C_p \) : Specific heat at constant pressure  
\( T \) : Absolute temperature

A change in the sum of the principal stress (\( \Delta \sigma \)) is obtained by measuring temperature change (\( \Delta T \)) using the infrared thermography.


In the self-reference lock-in thermography, a reference signal is constructed from the reference region arbitrarily set on the same sequential infrared images on thermoelastic temperature change. Distribution of relative intensity of the thermoelastic temperature change against that in the reference region can be obtained by the following least squares approach even under the random loading, provided that the temperature change in the reference region has the similar and in-phase waveform as the objective area of the measurement.

Assume that a body is subjected to a random loading whose waveform is expressed as \( f_n \). The infrared signal in an objective region can be approximated as follows.

\[ Y_n = a + b f_n \]  
(2)

Where \( a \) is the DC offset, \( b \) is an influence coefficient of the reference, \( n \) is the frame number. To calculate the influence coefficient, the square sum of deviations between \( Y_n \) and infrared signal \( y_n \) obtained from the region defined as follows is minimized.

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

Where \( N \) is the total frame number. Then, \( b \) is obtained by the following equation.

\[ b = \frac{\sum y_n - \frac{1}{N} \sum f_n \sum y_n f_n}{\sum f_n - \frac{1}{N} \sum f_n^2} = \frac{N \sum y_n f_n - \sum y_n \sum f_n}{N \sum f_n^2 - (\sum f_n)^2} \]  
(4)

When this calculation is performed on all the pixels of infrared thermography, it is possible to obtain the correlation between the infrared signal in reference region and that in any region. Values of \( b \) indicate a relative intensity of thermoelastic temperature change against that in the reference region. The self-reference lock-in method does not require any external reference signals and can be applied even under the random loading. Obtained values of \( b \) are effectively employed for detection of stress concentration area around notches or cracks.


4.1. Laboratory Test – Plate Specimen

Crack detection by the self-reference lock-in thermography is performed for welded specimens as shown in Fig. 1. 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. 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 set to be 10 Hz, and amplitude of the applied stress was 100 MPa. The thermoelastic temperature change was measured by the infrared camera with InSb focal plane array detector.
Figure 2 shows the experimental results obtained by the self-reference lock-in thermography in the process of crack propagation under the cyclic loading. Data were taken at stress amplitude of 100MPa and loading frequency of 10Hz. When a crack was relatively small as in Fig. 2(a), 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 Fig. 2(b), the singular stress field in the vicinity of the crack tips is clearly observed. This singular stress field becomes clearer with crack growth, since larger thermoelastic temperature change is observed at the crack tips.

4.2. Laboratory Test – Steel Structure

The crack detection by the self-reference lock-in technique was performed for a steel structure with trough ribs which simulated an actual bridge structure as shown in Fig. 3. 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. A crack is detected in the region “C” and “D” in Fig. 3. There was a central crack in region “C” and an edge crack in region “D”. Figure 4 shows the result obtained by the self-reference lock-in technique. The arrows in Fig. 4 indicate the singular stress field in the vicinity of the crack tips. The singular stress field in the vicinity of the crack tip is clearly detected. This fact should be taken into account in application of the self-reference lock-in technique to actual structure because the similar condition is expected in actual structures.

4.3. Fatigue Crack Detection in Steel Bridges

A schematic illustration of a part of the steel bridge reinforced by trough ribs is shown in Fig. 5. There are two different types of fatigue cracks that propagate from the weld root. Crack A initiates at the weld root and propagates through the weld throat. This type of fatigue crack can be called as “weld-bead penetrant type” fatigue crack. On the other hand, Crack B initiates at the weld root and propagates through the deck plate. This type can be called as “through-deck type” fatigue crack. The through deck type fatigue crack is not open to the inspection surface; therefore it is very difficult to be detected.
4.3.1. Detection of weld-bead penetrant type fatigue cracks in actual steel deck

Detection of weld-bead penetrant type fatigue cracks in a steel deck of the actual bridge was conducted by the self-reference lock-in thermography. Distribution of thermoelastic temperature change near the fatigue crack tip was measured under the variable wheel loading caused by the traffics on the bridge.

The experimental result obtained by the self-reference lock-in thermography was shown in Fig. 6. The reference region for generating the reference signal of lock-in processing was set at “R” in the figure. The location of the fatigue crack tip was indicated by the arrow in Fig. 6. It is found that significant contrast change can be observed at the crack tip due to the singular stress field in the vicinity of the crack tip. It is found that the location of the fatigue crack tip is clearly detected by the present technique.

Remote detection of fatigue cracks in steel deck in actual steel bridge in-service was conducted by the self-reference lock-in thermography with telescope lens as shown in Fig. 7. Infrared measurement was conducted from distant places in distances of 8m and 12m. Thermoelastic temperature change near the crack tip under variable wheel loading by the traffics on the bridge was measured by infrared camera. The experimental results obtained by the self-reference lock-in thermography are shown in Fig. 8. The region for generating the reference signal of lock-in processing was indicated by “Ref.” in the figure. The location of the fatigue crack tip was indicated by arrows in Fig. 8. It is found that significant contrast change can be observed at the crack tip due to the singular stress field in the vicinity of the crack tip. It is found that the
location of the fatigue crack tip is clearly detected from remote place by the present technique. It is also found that the crack could be detected in spite of degradation due to infrared attenuation by optical system of telescopic lens.

![Fig. 6 Result of self-reference lock-in measurement for crack detection in actual steel bridge](image)

**Fig. 6 Result of self-reference lock-in measurement for crack detection in actual steel bridge**

![Fig. 7 Self-reference lock-in measurement with telescopic lens for actual steel bridge](image)

**Fig. 7 Self-reference lock-in measurement with telescopic lens for actual steel bridge**

![Fig. 8 Result of crack detection in actual steel deck from distant place](image)

**Fig. 8 Result of crack detection in actual steel deck from distant place**

### 4.3.2. Detection of through-deck type fatigue cracks

Detection of through-deck type fatigue cracks by the self-reference lock-in thermography was conducted for a steel bridge specimen. The steel bridge specimen which simulated a part of the actual steel deck of the bridge is shown in Fig. 9. The thickness of the deck plate was 19 mm. Dimensions of cross section of the trough rib were indicated as U320×240×6; i.e., top width, height and thickness were 320 mm, 240 mm and 6 mm, respectively. Fatigue test was conducted for the steel deck specimen under the cyclic bending load of 10 - 110 kN as shown in Fig. 10. Load frequency was set to be 9 Hz.

Distribution of thermoelastic temperature change was measured by the infrared thermography and obtained sequential infrared data were processed by self-reference lock-in technique. A fatigue crack was initiated from the back surface of the weld bead and propagated to the deck plate; however it was not open to the inspection surface. The result of
the self-reference lock-in processing was shown in Fig. 11. The reference region for generating the reference signal of lock-in processing was set at "Reference signal" in the figure.

Characteristic stress concentration in the deck-to-rib weld bead was not shown in the early stage of fatigue testing as shown in Fig. 11(a) and (b). On the other hand, significant stress concentration zone in the weld bead were found in Fig. 11(c) and (d), and it moved from cross rib to the left in the figure. It was found that significant stress concentration zone can be observed near the crack front, which enabled us to detect through deck type fatigue cracks. It was also found that half length of the fatigue crack can be estimated from the distance between the center of stress concentration zone and the cross rib.
Comparison of crack length measurement between the self-reference lock-in thermography and the ultrasonic inspection is shown in Table 1. It was found that crack length can be accurately determined by the present technique.

Table 1 Comparison of crack measurement between self-reference lock-in thermography and ultrasonic inspection

<table>
<thead>
<tr>
<th>Number of Load cycles</th>
<th>Distance from cross rib to stress concentration zone obtained by the self-reference lock-in thermography</th>
<th>Distance from cross rib to semielliptical crack tip obtained by ultrasonic inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>500,000</td>
<td>Difficult to determine</td>
<td>17 mm</td>
</tr>
<tr>
<td>1,000,000</td>
<td>35 mm</td>
<td>34 mm</td>
</tr>
<tr>
<td>2,000,000</td>
<td>40 mm</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

5. Conclusions

The practicability of the nondestructive evaluation technique based on the thermoelastic stress analysis for fatigue cracks in aging steel bridges was examined. Crack detection by the self-reference lock-in thermography developed by the present authors was conducted for fatigue cracks in actual steel bridges. It was found that self-reference lock-in thermography was practicable for detection of different types of fatigue cracks, such as weld-bead penetrant type crack and through-deck type crack.

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REFERENCES
