Development of nondestructive crack inspection technique for steel structure using Thermoelastic effect

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Abstract

In recent study, active thermography has reached a high status as an easy and speedy defects inspection method in a NDT field. This paper newly proposes a remote and efficient NDT method using a Thermoelastic effect technique for detecting and evaluating of fatigue cracks at the beam girder in the overhead traveling crane.

When the crane moves with the heavy load, the beam girder is subjected to variable load from running wheel of the crane. It applies the fluctuating stress to the beam girder. In this case, the high stress is occurred in the crack tips because of the stress concentration. On the other hand, there is no stress in the crack because it is not fixed. Therefore using Thermoelastic effect, the crack is detected as combination high temperature amplitude area with low temperature amplitude area by thermography. In this method, the crack is detected without setting up the scaffold and stopping the line, because this fluctuating stress is generated by the routine crane operation.

And Self reference lock-in data processing technique is applied for improvement of signal noise ratio in the crack detection process. This technique makes it possible to perform correlating process without an external reference signal. Time and cost saving inspection method in the beam girder is carried out using this NDT technique.

Keywords: Thermoelastic effect, crack, lock-in thermography

1. Introduction

A large number of an overhead traveling crane is generally installed in the steel making plant. Mainly it is composed of the beam girder, the crab trolley and the runway girder. The load is handled by the crab trolley moving on the beam girder. And the beam girder runs on the runway girder.

In the case of the overhead traveling crane failure, the steel production is stopped and the huge loss is happened because there is no backup machine. Therefore the overhead traveling crane is inspected regularly by the MT method, the UT method and the visual check using the scaffold. Because it is necessary to fold the scaffold and approach the structure when these methods are applied, the crane must be stopped running during inspection. Folding the scaffold is time and cost-consuming. And these inspections in the high place have a risk of the worker’s fall accident.

In this paper, a high efficiency and remote crack inspection technique for overhead traveling crane is studied using the thermoelastic effect, which is one technique for detecting structural damage using infrared thermography.
2. Principle of Thermoelastic effect

The temperature of a gas decreases when the adiabatic expansion occurs, and conversely, its temperature increases under adiabatic compression. In solids, a similar phenomenon is known to occur as a result of sudden stress. This is generally called the thermoelastic effect. In metals and other homogeneous materials, heat generation by the thermoelastic effect can be expressed by Eq. (1)

\[ \Delta T = -K \cdot T \cdot \Delta \sigma \] (1)

where, \( \Delta \sigma \) is the change in the sum of principal stresses, \( T \) is the absolute temperature, and \( K \) is the thermoelastic coefficient. The thermoelastic coefficient is a characteristic value of each material, and for mild steel, \( K = 3.5 \times 10^{-12} \text{ Pa}^{-1} \).

In the crack inspection and the stress measurement using the thermoelastic effect in Eq. (1), the small temperature change when a stress change occurs in the object is measured by high resolution infrared thermography (temperature resolution: 0.02 K), and the stress value is then calculated based on Eq. (1). When a crack exists in the object, a stress concentration will occur at the tip of the crack, and it is possible to detect the crack as a temperature anomaly. The next section introduces the self reference lock-in method, which is a signal processing method that is applied to improve S/N ratio.

3. Basic Principle of Self Reference Lock-in Processing

Figure 1 shows schematic diagrams of the conventional lock-in method and the self reference lock-in method used in this paper. The conventional lock-in method is a signal processing method in which a reference signal such as a load signal, etc. is obtained from the tester, a signal with the same frequency as the reference signal is extracted from the time-series temperature change measured by infrared thermography, and the S/N ratio (signal to noise ratio) is improved. However, application to actual equipment is difficult because a random stresses act on the object of measurement, and there are also many cases in which a load signal cannot be obtained as a reference signal. On the other hand, the self reference lock-in method uses temperature changes of a reference area in the infrared image. As described in the previous section, a linear correlation exists between stress change (load change) and temperature change. This means their change frequencies are the same. Therefore, even in cases where a load signal cannot be obtained, as in actual equipment, it is possible to obtain an S/N improvement effect similar to that in lock-in processing by using the temperature change in the infrared image as a reference signal.

![Schematic diagrams of the conventional lock-in method and the self reference lock-in method](image-url)

Fig.1 Schematic illustration of signal processing method
4. Result of Laboratory test

This section introduces the laboratory test of detecting cracks using thermoelastic effect. First, the minimum stress for crack detection is investigated using a test sample prepared by partially cutting an actual beam girder. A schematic illustration of the test is shown in Fig. 2. A fatigue crack is introduced in the weld toe of the triangular rib in the cut sample. A stress waveform which attenuated while vibrating from stress amplitude of 100 MPa to 10 MPa is loaded on this sample using a sine waveform with a frequency of 2 Hz. Infrared thermography measure the test sample at a distance of 15.3 m using a telephoto lens with a focal length of 200 mm. The applying stress is measured by a strain gauge attached to the test sample.

Figure 3 shows the stress distribution images at stress amplitudes of 100 MPa, 50 MPa, 20 MPa, and 10 MPa. The results of this experiment showed that the crack tip can be detected as a high temperature area (shown in white) in the crack areas (enclosed with solid lines in Fig. 3). Next, Fig. 4 shows the correlation of stress amplitude and temperature rise. The straight line is a theoretical solution for the thermoelastic effect shown by Eq. (1). As the plots for the stress and the temperature rise are approximately on the straight line shown as the theoretical solution, it shows the measured temperature rise can be converted to the stress apply to the test sample with high accuracy.

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**Fig. 2** Schematic illustration of the test in the laboratory (Offline test)

**Fig. 3** Infrared image around cracks in various stress applied
(Max. stress = 100, 50, 20 and 10 MPa)
5. Result of actual structure

Based on the results obtained in the laboratory tests, as described above, a remote crack inspection test by this method is applied to a box beam girder in an overhead traveling crane scheduled for repair. A schematic illustration of this test is shown in Fig. 5. A crab trolley is mounted on the beam girder for load hoisting, and traversing is possible. The load applying on the wheels of the crab trolley is the total of the dead weight of the crab trolley and the suspended load (80% of rated load). The stress fluctuations applying to the beam girder were measured as the small temperature change by an infrared thermography installed on the ground while the crab trolley traverses the beam girder in several times. The distance between the measurement surface and the infrared thermography on the ground is approximately 23 m.

An overall view of a stress distribution image measured with the infrared thermography is shown in Fig. 6 (a), and an enlargement of the crack area is shown in Fig. 6 (b). The high stress area (shown in white in Fig. 6) is detected on the right side of the triangular rib (enclosed with solid line) because of the stress concentration on the crack tip. Figure 7 shows line profile of the stress in the crack area shown in Fig. 6 (b). As stress increases sharply at crack tip ($\alpha$) and crack tip ($\beta$), the stress concentration on the crack can be measured clearly. On the other hand, the stress between the two crack tips is virtually zero. it shows neither compression nor tension is applied in that area. This is because the crack opening is not mechanically constrained except at the crack tip and no stress is applied in the area.

Next, Fig. 8 shows the time-series stress change measured by infrared thermography. It shows that stresses approximately from 30 MPa to 80 MPa applied on the sound part (reference area in Fig. 6) when the crab trolley passed over the measurement area 3 times. The stress under the 80% loading condition in this test is calculated at 30–60 MPa by finite element method (FEM) analysis, showing that it is possible to measure stress with high accuracy. On the other hand, large stresses from 100 MPa to 180 MPa applied on the crack tip due to stress concentration. In the stress curve for the crack tip, two peaks are detected in each pass. This shows that stress reaches its maximum in the instant when the two wheels of the crab trolley passed over the crack tip.

As described above, it is possible to obtain the crack length from 2-dimensional data and stress fluctuations from time-series change data.
Figure 9 shows the results of improvement of the $S/N$ ratio using the self reference lock-in method. The stress fluctuation of the reference area in Fig. 6 (a) is used as the reference signal. The $S/N$ ratio improved remarkably, and it is also possible to detect the stress concentration at the tip of the triangular rib.

As shown by this explanation, the possibility of remote crack inspection of the overhead traveling crane by the thermoelastic effect using loading fluctuations of the force is verified.

Fig. 5 Schematic illustration of online test
(Box beam girder of Relationship between stresses measured)

Fig. 6 Stress distribute in box beam girder of overhead crane system (no signal processing)
Fig. 7 Stress line-profile in line A-A’ shown in Fig. 6 (b)

Fig. 8 Comparison of Stress change between crack tip and sound area (“Reference area” shown in Fig. 6 (a))

Fig. 9 Image of stress distribute after signal processing (self reference lock-in method)
6. Conclusion

In this study, the crack inspection using the thermoelastic effect, which is a technique using infrared thermography, was applied to the overhead traveling crane. The following results were obtained.

(1) The correlation of stress amplitude and temperature rise is approximately same as the theoretical solution, it shows the measured temperature rise can be converted to the stress apply to the structure with high accuracy.

(2) The stress calculated by finite element method (FEM) analysis in the sound area and measured by the infrared thermography is approximately same. It shows that it is possible to measure stress with high accuracy. On the other hand, The crack tip can be detected as a high temperature area. So in the stress curve for the crack tip, two peaks are detected in each pass. This shows that stress reaches its maximum in the instant when the two wheels of the crab trolley passed over the crack tip. As described above, it is possible to obtain the crack length from 2-dimensional data and stress fluctuations from time-series change data.

(3) The S/N ratio is improved remarkably using self reference lock-in processing, if the stress applied to the structure is not measured directly.

References


