Application of Infrared Thermography to Detection of Cracks*

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We have developed an experimental and computational hybrid measuring system for the purpose of nondestructive detection of cracks embedded in the structural members. The system consists of an infrared thermal video system (TVS-5000), by which the temperature distribution of a body surface can be measured, and an engineering work station (EWS), by which image processing of the thermal image can be carried out. Various methods for heating or cooling the specimen have been examined. Further more, an image-processing expert system has been developed to obtain definite images of the defects.

Key Words: Nondestructive Inspection, Expert System, Image Processing, Detection of Cracks, Hybrid System, Infrared Thermography

1. Introduction

There are many methods widely used for the detection of the cracks, such as ultrasonic, radiographic, magnetic particle, and penetration tests. However all of these require much inspection time and labor in crack detection of large-scale structural members. The aim of this study is to develop a simpler and more convenient method for the detection of cracks. We have studied the possibility of developing a new method using infrared thermography⁽¹⁾⁻⁽⁴⁾.

In recent years, many types of infrared video systems have been used in various fields of industry. They are essentially devices for measuring temperature distribution of a body surface. Therefore, the mechanism for detecting cracks using this device is to determine the specific pattern of a thermogram caused by cracks. There are two essential problems to

be overcome to realize a method useful for practical applications. They are (1) the problem of assigning the suitable temperature gradient to specimens or real structural members with cracks, and (2) the problem of image processing to extract crack patterns from the raw, complicated thermogram which includes many patterns other than those of cracks.

In this paper, we have dealt with these two problems.

2. Development of the Crack Detecting System

In order to detect the cracks efficiently, we have developed an experimental and computational hybrid system which consists of a thermal video system, TVS-5000, to take the thermogram of the body surface, and an engineering work station, NEWS, to carry out image processing. Data from thermography using TVS-5000 can be accessed to EWS through a personal computer, PC-9801, as shown in Fig. 1.

The infrared video system used in the experiment is the TVS-5000 developed by Nippon Avionics Co., Ltd. Infrared rays emitted from the surface of a body can be detected by the infrared detector made of In-Sb, and the temperature distribution is reconstructed

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as a visual image by the image processor. The main specifications of the TVS-5000 are shown in Table 1.

The detector, by which the intensity of the infrared ray emitted from the body surface can be detected, has 10 rotating mirrors and 10 detecting elements. Sufficient and essential information required by a thermogram in the visual range can be obtained by a single rotation of the rotating mirrors. The mirrors rotate at 20 rotations/s; thus the thermogram signals for one frame can be obtained every 0.05 seconds.

In the image processor, the amplified signals from the infrared detector are transformed into digital quantities of 8 bits, i.e., 256 levels by means of the A/D transformer, and then they are stored in the frame memory. One frame consists of 256(vertical) $\times$ 199(horizontal) pixels with each pixel having a depth of 1 byte (8 bit, 256 colors). Signals in the frame memory can be read out sequentially based upon the synchronized TV signals, and they are expressed on the color monitor as a thermal image. The thermal image data for one frame (256 bytes/line $\times$ 199 lines = 50 944 bytes) with time and temperature range data (300 bytes) can be recorded on a floppy disk and the information of one frame is composed of 51 244 bytes. These data can be read and accessed to the engineering work station NEWS where they are used for further picture image.

The engineering work station used in the study is NEWS-3460 developed by Sony Co., Ltd. The main

specifications are :

Main memory	: 8 MB
Main processor	: R 3000
Floating point accelerator	: R 3010

The color TV monitor can express 256 colors at the same time; therefore, it is compatible with the color monitor of TVS-5000.

3. Comparison of Heating or Cooling Methods

In order to detect cracks using infrared thermography, it is necessary to give the specimen a temperature gradient. There are many methods for heating or cooling the specimen. Each method gives its own characteristic thermogram of the cracked specimen depending upon the method of heating or cooling. Therefore, it is necessary to determine the most effective method for detecting cracks, in particular, fatigue cracks.

We have studied six different methods :

- (1) plastic-induced heat generation ;
- (2) laser heating ;
- (3) heating by high-frequency eddy current ;
- (4) heating by alternating current ;
- (5) heating by hot blow ; and
- (6) spot cooling by a cooling agent.

We have already reported on about the first method⁽¹⁾, the results of which will also be given here for comparison with other results.

3.1 Plastic-induced heat generation

A servo-hydraulic fatigue machine was used as the loading unit. After a certain amount of fatigue crack propagation was confirmed in the specimen, the real time thermograms of the specimen surface were monitored by TVS and recorded in the VTR. At the same time, load signals from the fatigue machine were synchronized and stored in the frame recorder with the thermogram data of maximum and minimum loadings.

Figure 2 shows the thermogram of the slit specimen subjected to the fully reversed load of $\Delta P = 1.47 \times 10^4$ N. A fatigue crack can be observed to initiate at the root of the slit. Marked heat generation due to cyclic plastic deformation is observed at the tip of the fatigue crack.

In this method, the heat generation is induced by plastic deformation caused by mechanical cyclic loading, thus, it is possible to detect a fatigue crack by this method when the cracked members are just under the cyclic loads.

Generally, however, the method has the following shortcomings :

- (1) a special loading device is necessary to obtain the thermogram ; and

Table 1 Main specifications of the TVS-5000

	TVS-5000
Temperature range	-40~280°C
Sensitivity	0.05°C
Field of view	10° $\times$ 15°
Frame time	0.05sec
Picture resolution	256 $\times$ 200

Fig. 1 The hybrid system for crack detection

- (2) the load necessary for detection of cracks is sometimes so large as to cause failure of the specimens.

3.2 Laser heating

Figure 3 shows the crack inspection system utilized in the laser heating method. The laser emitted from the YAG laser oscillator (maximum output 20 W) is applied to the specimen surface via the scanning mirror, causing heat generation around the spot irradiated by the laser beam (beam spot).

The beam spot can scan the entire specimen surface by changing the angle of the scanning mirror driver via the function generator. The thermograms of this temperature change are monitored by the TVS and are recorded on video tape and on the real time recorder every 0.1 seconds.

Figure 4 shows a thermogram of the specimen with a semielliptical surface slit of depth $a=4$ mm and

width $2c=20$ mm, when the focused beam is applied to one side of the surface slit. The temperature distribution observed is discontinuous across the slit because heat conduction is prevented by the slit.

Figure 5 shows the edge-processed picture of the

Fig. 2 A thermogram of the slit specimen with a fatigue crack

Fig. 4 A thermogram of the surface-notched specimen taken by the laser heating method

Fig. 3 The crack inspection system by the laser heating method

Fig. 5 The edge-processed picture of the thermogram in Fig. 4

above thermogram. The gradient of the temperature along each line of the frame can be expressed by edge-processing. Discontinuity, such as cracks or slits, can easily be detected through edge-processing.

The laser heating method enables crack detection at a short time from a distance, but it also has the following shortcomings:

- (1) short, closed fatigue cracks are not detected with ease;
- (2) a large-scale inspection system is necessary; and
- (3) the high-energy laser is dangerous in practical use.

3.3 High-frequency eddy current heating

As shown in Fig. 6, the cracked specimen is set at a distance of about 10 mm from the coil through which the high-frequency electric current is applied. The temperature change at the surface of the specimen raised by the eddy current is detected by the infrared camera set on the other side of the coil, and the real-time thermogram is monitored on the color TV monitor. These thermograms are stored on the floppy disk and video tape.

Figure 7 shows a thermogram of the CT specimen

Fig. 6 The crack inspection system by the high-frequency heating method

Fig. 7 A thermogram of the detected fatigue crack by the high-frequency heating method

with a fatigue crack of about 4 mm which is heated by the high-frequency electric current. The fatigue crack has been generated under the same conditions as those mentioned in the previous section. The crack closes and its surfaces come into contact during unloading when the inspection is carried out.

A remarkable increase in temperature is observed on the thermogram at the part of the fatigue crack, i.e., near the center of the coil. This may be due to the high resistance of the closed fatigue crack against the electric current. Therefore, it is possible to detect the pattern of heat generation due to the crack, in particular, the fatigue crack, by TVS and to detect the position and size of the crack.

This method is effective because small fatigue cracks can be detected although a special high-frequency heating device is required. The shortcoming of this method is that the surface of the specimen has to be flat because the degree of heat generation, i.e., the density of the high-frequency eddy current, is very sensitive to the distance from the coil to the specimen surface. Therefore, it is difficult to detect the cracks along the welding line.

3.4 Alternating current heating

Alternating current is directly supplied to the specimen by setting the electrodes on both ends of the specimen (see Fig. 8). If there is a slit in the specimen, the flow of current is prevented, thus the current will concentrate at the tip of the slit, resulting in a marked heat generation at the tip. The frequency of the alternating current and the voltage were set at 50 Hz and 2 V, respectively. Figure 9 shows the thermogram taken by this method. Since a marked heat generation occurs at the tip of the slit, it is easy to determine the size of the slit. However the difficulty lies in connecting the electrodes to the specimen because a large-scale alternating current is supplied. Ogura and Sakagami⁽⁵⁾ have carried out an experiment using this method and shown that the method is useful.

3.5 Heating by hot blow or spot cooling

This method involves heating or cooling by a portable hot blow or spot cooling instrument (see Fig. 10). Hot blow is effected by the generation of heat

Fig. 8 The crack inspection system by the alternating current heating method

from the catalytic oxidation reaction of liquefied butane gas, while spot cooling is carried out by blowing out fluorocarbon gas through the nozzle of the

Fig. 9 A thermogram of the surface-notched specimen taken by the AC current heating method

Fig. 10 The crack inspection system by the hot blow and spot cooling methods

Fig. 11 A thermogram of the slant slit specimen with a fatigue crack taken by the hot blow heating method

spray.

Figure 11 shows the thermogram taken by the hot blow method. A fatigue crack exists at the tip of the slant slit as shown in Fig. 11. The thermogram shows that heat conduction is prevented by both the slit and the fatigue crack. A similar thermogram pattern can also be obtained by spot cooling. In the case of spot cooling, however, the cooling agent sometimes penetrates into the crack which results in a specific pattern shown in Fig. 12.

The merit of this method is that we do not need large-scale devices as mentioned above, that is, loading machine, laser equipment or electric devices for high-frequency or alternating current. Since the hot blow and spot cooling instruments are portable, they are easy to handle. However small fatigue cracks, which can be detected by the high-frequency eddy current technique, are difficult to detect by this method.

4. Development of the Image Processing Expert System

As shown in images presented in the previous section, the raw thermograms are complicated because they depend upon the heating or cooling systems, and much thermal information other than

Fig. 12 A thermogram of the CT specimen with a fatigue crack into which the cooling agent has penetrated

that of cracks are included. Therefore, only experts can judge whether or not there is evidence of cracks by visual inspection of thermograms. It is therefore useful to develop an expert system the image processing to extract cracks from the original thermograms.

We have developed an image-processing expert system which is equipped with "the knowledge on the techniques of image processing that experts possess." The system is an application of the so-called expert system, which is making remarkable progress in the field of intellectual engineering, to the image processing of the thermogram. The developed system consists of the following two subsystems:

- [1] the system in which the algorithm involved in image processing such as feature extraction and region segmentation is automatically chosen and processed;
- [2] the interactive consultation system which gives the users instructions and advice on image processing.

We have developed a program to carry out image

Fig. 13 Flow of image processing using the developed expert system

Fig. 14(a) The raw thermogram of the CT specimen with a fatigue crack heated by the high-frequency eddy current

Fig. 14(b) The result of image processing of the thermogram in Fig. 14(a)

Fig. 15(a) The raw thermogram of a honeycomb structure

Fig. 15(b) The result of image processing of the thermogram in Fig. 15(a)

processing for crack detection efficiently and accurately. It is written using the C language and CGI (Computer Graphics Interface) and mounted on the EWS. In the development of the program, we have prepared first unit programs corresponding to various elementary processes such as smoothing, elimination of noise, and so on. Then, we stored knowledge and experience about the effects and features of these elementary processes by applying them to the image processing of the real thermograms. In practice, some of these elementary processes are put together in one set, and the processing of the set is carried out repeatedly. The above procedure is called "the general processing procedure." Further more, there is a problem of how to determine the most suitable values for the parameters that appear in a series of programs of image processing. This is called "the decision of particular processing procedure." We have extensively studied both procedures. Finally, by assembling these procedures, we have constructed an image-processing expert system called EXPRODEC (EXpert PROgram for DETecting Cracks) to assist in the detection of cracks by infrared thermography.

Figure 13 shows the flow of the developed expert system.

The following examples show how the developed system works effectively. Figure 14(a) shows the raw thermal image of the CT specimen with a fatigue crack heated by the high-frequency eddy current. Figure 14(b) shows the result of image processing where the expert system was applied.

Figure 15(a) shows the raw thermogram of the honeycomb sandwich structure which is constructed by the aluminum honeycomb covered with CFRP sheets on both sides. Usually, the honeycomb structure cannot be observed from the outside because it is covered with CFRP sheets. However when we heat one side of the honeycomb structure and observe it from the other side through the infrared camera, we can obtain a thermogram such as that shown in Fig. 15(a). Figure 15(b) shows the result of image processing by the developed expert system. The honeycomb structure can be observed more clearly, and therefore, it is possible to detect defects such as imperfection of bonding if they exist in the structure.

5. Conclusions

We have developed an experimental and

computational hybrid measuring system for the purpose of nondestructive detection of cracks embedded in the structural members. The system consists of an infrared thermal video system (TVS-5000), by which the temperature distribution of a body surface can be measured, and an engineering work station (EWS), by which the image processing of the thermogram can be carried out.

Various methods for heating or cooling the specimen have been examined and compared. Furthermore, an image-processing expert system has been developed and the system is found effective to obtain definite images of the defects.

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