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ACTIVE THERMOGRAPHIC INSPECTION COMBINED WITH LASER CYCLIC HEATING AND FOURIER TRANSFORM PROCESSING.

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ABSTRACT

In this study, active thermographic inspection of CFRPs using laser cyclic heating combined with Fourier transformation technique was examined. By using long-time cyclic heating, large heat energy is input into the test objects at a specific frequency that agrees with the cyclic heating frequency. Then, the specific frequency component is extracted by Fourier transform. By using the transformed data, higher inspection capability than the conventional active thermographic methods (such as pulse thermography) should be achieved. Results of experiments for a CFRP specimen with some artificial defects showed that defect detectability was significantly improved in phase images constructed from the Fourier transformed data when its frequency corresponds the frequency of cyclic heating. These results suggest the proposed method is a promising way for convenient active thermographic inspection technique with high inspection capability.

Keywords: Active thermography, CFRP, Fourier transform, Laser heating

1. INTRODUCTION

Active infrared thermographic nondestructive testing is one of well-known inspection method of composite material (such as carbon fiber reinforced plastics: CFRPs). In this method, test object is heated by using a heater (such as halogen lamp, or xenon flash lamp, etc.), and its surface temperature after heating is monitored by an infrared camera. When a defect (such as delamination) is included in a test object, heat flow from the heated surface is disturbed by the defect, and local inhomogeneous temperature region is occurred near the defect and, also in the object surface; by detecting the inhomogeneous temperature region, the internal defect is identified. In addition to the conventional active thermographic inspection, lock-in thermography is an alternative method used for improving the inspection capability [1-3]. In the lock-in thermography method, test objects are heated cyclically, and phase angle data are obtained by correlating the observed temperature oscillation with the input cyclic signal. The phase angle influenced by the internal defects; thus, defects can be identified by detecting phase difference between the defective and nondefective area.

This study deals with the inspection of CFRP laminates using the active thermography method, and also focuses on using the phase angle data in order to achieve high-accuracy inspection. In this study, in order to obtain phase data more conveniently, Fourier transformation technique was used; discrete Fourier transformation was applied to the temperature-time data observed after cyclic heating, and phase-frequency data $\varphi(f)$ were obtained from the following equation:

$$\varphi(f) = tan^{-1}\frac{I(f)}{R(f)} \quad (1)$$

where, f denotes frequency, and $R(f)$ and $I(f)$ are the real and imaginary component calculated from Fourier transform, respectively. This technique is called as pulse phase thermography method when instantaneous pulse heating is used [4-6]. By using the long-time cyclic heating instead of the pulse heating, a higher heat energy is input into test objects, especially at a frequency that corresponds to the cyclic heating frequency. Thus, by using the phase data at the specific frequency, the defect detection capability should be improved. This study investigates the effectiveness of the above-mentioned method through experiments. Inspections using cyclic heating for a CFRP specimen with some artificial defects is performed, and defect detection capability obtained when using conventional temperature data and when using phase data at the specific frequency are compared. In the experiments, a semiconductor laser equipment is used for heating the specimen in order to well control the cyclic heating period.

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2. EXPERIMENTS

Experiments for a CFRP specimen was performed in order to examined the defect detection capability of the proposed method.

2.1 Experimental setup

Experimental setup and a CFRP specimen used in the experiments are shown in Fig.1 and Fig.2, respectively. The CFRP specimen is 100 × 100 × 4 mm, and is unidirectionaly reinforced with PAN-based carbon fiber (T700SC, TORAY Industries, Inc.). The specimen has some flat-bottom holes as artificial defects; defect size φ is 10, 5, and 2 mm in diameter, and defect depth t from heated surface is 0.5, 1.0, 1.5, and 2.0 mm (see Fig. 2). A semiconductor laser equipment (wavelength about 800 nm, PB256-C, Changchun New Industries Optoelectronics Technology Co., Ltd.) was used as a heat source, and cyclic heating was controlled using a function generator (AFG3102, Tektronix Co., Ltd.). The distance between the laser head and the specimen was 20 cm, and the laser output power was 3 W. In the experiment, surface of the specimen without holes (flat surface side) was heated, and temperature on the same surface was monitored by an infrared camera (A315, FLIR Systems, Inc.) with sampling frequency of 15 Hz. The cyclic heating frequency was 0.05 Hz. The obtained temperature-time data were Fourier transformed into phase-frequency data, then phase image at the same frequency of the heating frequency was constructed.

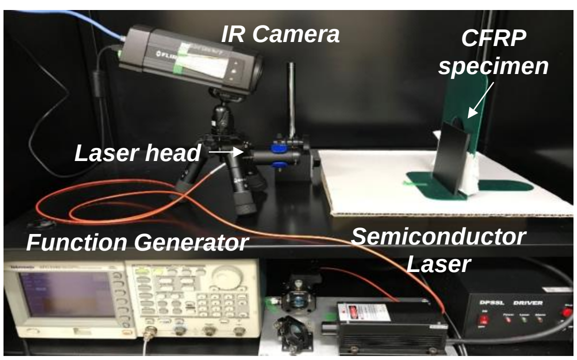

FIGURE 1: EXPERIMENTAL SETUP USING LASER CYCLIC HEATING.

2.2 Experimental results

Figure 3 shows the temperature image observed during heating, and Fig. 4 shows temperature-time data obtained on the defect of t = 0.5 mm and φ = 10 mm. It is found from these figures that the surface temperature oscillates according to the heating cycle, and defective areas are displayed as local hot (bright) area. However, in the temperature image, only a few defects (t = 0.5 and 1.0 mm for ϕ = 10 mm) were detected.

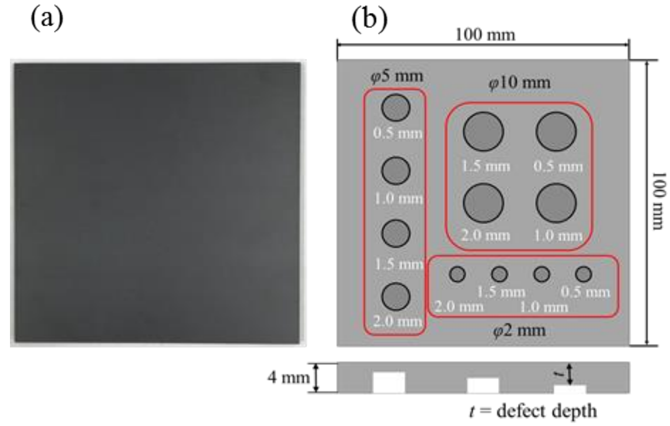

FIGURE 2: (a) CFRP SPECIMEN WITH ARTIFICIAL DEFECTS, AND (b) SCHEMATIC DIAGRAM OF THE SPECIMEN.

Figure 5 shows the phase images obtained by applying Fourier transform to the temperature data in the region enclosed by solid green lines in Fig. 3. In Fig. 5, phase images at three different frequencies are compared. As seen in this figure, defect detectability was significantly improved when the frequency is 0.05 Hz (i.e., the frequency agrees with the cyclic heating frequency). In the phase image at 0.05 Hz, defects which could not be detected in the temperature image (φ = 5 and10 mm for all t) can also be detected. Figure 6 shows the phase difference between the defective and sound areas on 10-mm-diameter defects as a function of frequency. It is found from Fig. 6 that the phase difference shows a significant change at 0.05 Hz. Figure 7 shows the SN (signal-to-noise) ratio on the 10-mm-diameter defects (the SN ratio was obtained by dividing the absolute value of the phase difference in Fig. 6 by the standard deviation of the phase noise in the sound area). As expected from Fig. 6, the SN ratio is significantly increased at 0.05 Hz. These results indicate that the defect detection capability is greatly improved by using the phase image when its frequency is corresponds to the cyclic heating frequency.

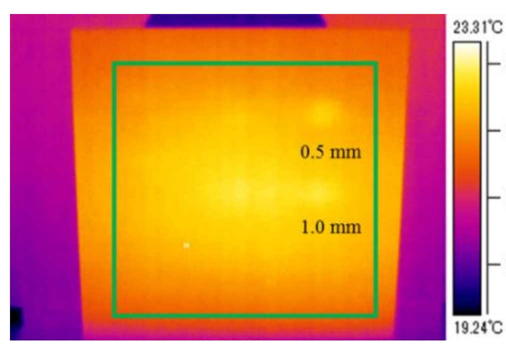

FIGURE 3: TEMPERATURE IMAGE OBTAINED USING LASER CYCLIC HEATING. NUMERALS IN THE IMAGE INDICATE DEPTH OF DEFECTS.

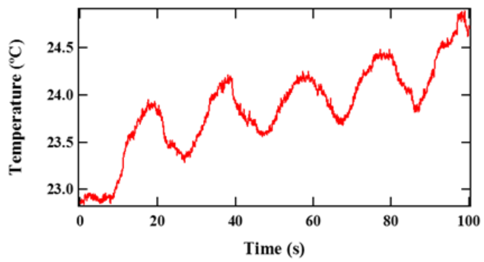

FIGURE 4: TEMPERATURE-TIME DATA OBSERVED ON SPECIMEN SURFACE.

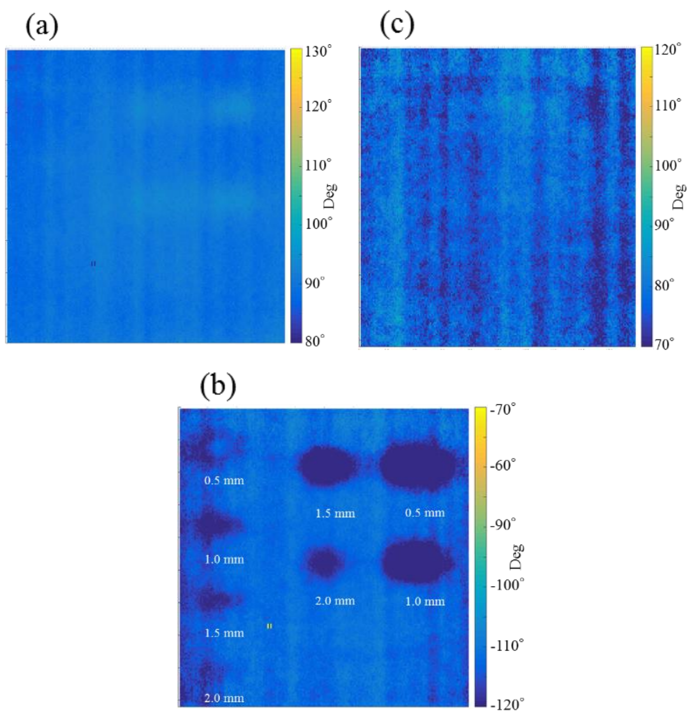

FIGURE 5: PHASE IMAGES AT FREQUENCY OF (a) 0.01 Hz, (b) 0.05 Hz (c) 0.10 Hz OBTAINED BY APPLYING FOURIER TRANSFORM TO THE TEMPERATURE DATA.

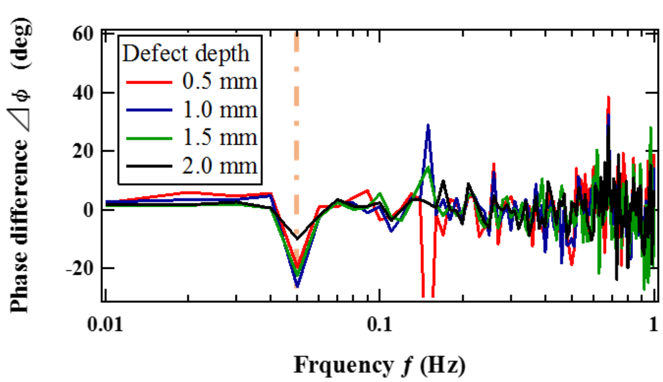

FIGURE 6: PHASE DIFFERENCE vs. FREQUENCY OBSERVED ON 10-mm-DIAMETER DEFECTS.

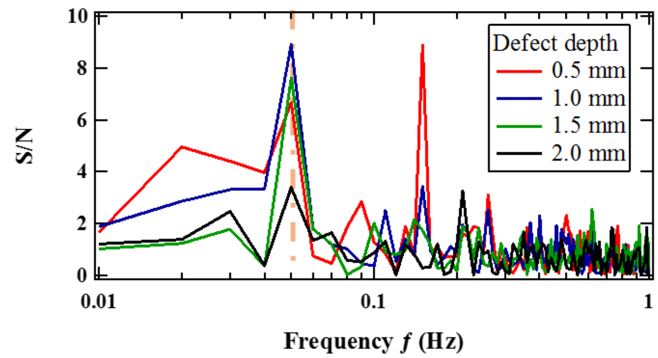

FIGURE 7: SN RATIO vs. FREQUENCY OBTAINED ON 10-mm-DIAMETER DEFECTS.

3. CONCLUSION

Inspection of a CFRP specimen by using infrared active thermographic method with cyclic heating was examined. As a result of the experiments, it is found that inspection capability is improved when using phase image which frequency corresponds to the cyclic heating frequency. These results suggest the proposed method should be an effective and convenient thermographic inspection technique. It should be noted that a laser equipment was used as a heat source in this study; the laser output can be easily and precisely controlled, and by adjusting the lens system (or using laser beam with top hat distribution), it is possible to make a uniform heating region. These advantages of using laser equipment also contributes to the high-accuracy inspections.

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