1 Introduction

Infrared thermographic non-destructive testing is a non-contact method, requires shorter inspection time than other techniques such as ultrasonic method. Due to these advantages, this method is also effective for testing CFRP (carbon fiber reinforced polymer) structures. The most conventional thermographic method is pulse thermograph (PT). In PT, surface of test object is instantaneously heated by flash lamps, and the surface temperature after heating is monitored by an infrared camera. If there is a defect inside the object, heat flow from the surface is disturbed by the defect, and an inhomogeneous temperature area appears on the surface. In some previous papers, PT was used for detecting defects in CFRP specimens, and the reported detectable defect depth was 2-3 mm [1,2].

In order to improve the detectable defect depth by thermographic techniques, pulse phase thermography (PPT) has been reported [3]. In PPT, the surface temperature data as a function of time obtained by PT is transformed to phase-frequency relation by applying Fourier transform, and phase images at each frequency are constructed instead of temperature images. The detectable defect depth depends on the frequency of phase images, and deeper defects are detected in lower frequency range [4]. Previous papers [5] reported defects in a CFRP specimen with depth of up to 5-6 mm were detected by PPT.

This paper aims to achieve further detectable defect depth using PPT, and for this aim we focused on noise appears in the phase data (phase noise). As with in the temperature images, the detectable defect depth in phase images depends on the amplitude of the noise. It is clear that decreasing the phase noise leads to enhance the detectable depth of defects. In this study, we examined two methods to decrease the phase noise. One method is to apply long-duration heating on behalf of the instantaneous pulse heating, and another is decreasing the influence of ambient temperature fluctuation. The effects of both methods were investigated by analytical and experimental studies.

2 Pulse phase thermography (PPT)

Figure 1 schematically presents the procedure of PPT. In PPT, surface of test sample is heated by heat sources, and the surface temperature as a function of elapsed time after heating T(t) is observed by an infrared camera, as with in PT method. Then, the temperature is Fourier transformed to phase-frequency relationship \( \phi(f) \) using following equation [3]:

\[
\phi(f) = \tan^{-1} \frac{I(f)}{R(f)}. \tag{1}
\]

Therein, \( f \) stands for the frequency, and \( R(f) \) and \( I(f) \) are real and imaginary components obtained using the Fourier transform, respectively. Using \( \phi(f) \), two-dimensional phase images at each frequency are constructed. Inside defects are detected by using phase difference between defective and non-defective surface appeared in the phase images.

3 Applying long-duration heating

Increasing heating duration can easily increase heat input, and this also enhances the temperature
difference between defective and non-defective area. Here we investigate the influence of the long-duration heating on phase data, and especially focus on relation between the phase noise and the heating duration.

3.1 Analytical studies

To examine the relationship between the heating duration and the amplitude of phase noise, one-dimensional analyses were performed. Analytical model used in the analyses is presented in Fig. 2(a). In this study, flat-bottomed hole like Fig. 2(b) is considered as simplified defects, and Fig. 2(a) simulates the circled area in Fig. 2(b). Based on an assumption that there is only one-dimensional heat transfer in the thickness direction in the circled area in Fig. 2(b), calculation results from Fig. 2(a) corresponds to the results for defects with infinite diameter located at a depth of $H$.

When applying long-duration heating with duration of $t_h$, the surface temperature ($T(t)$) is calculated as

$$T(t) = \frac{2Q}{h} \sum_{n=1}^{\infty} \frac{Bi}{B_i^2 + 2Bi + \mu_n^2} e^{n^2 Fo} \left(e^{n^2 F_{oh}} - 1\right). \quad (2)$$

Where, $t$ is elapsed time after heating [s], $\rho$ and $c$ respectively stand for density [kg/m³] and specific heat [J/(kg K)]. $B_i$ denotes the Biot number defined as $B_i = hH/k$ ($h$ denotes surface heat exchange coefficient [W/(m²K)] and $k$ represents the thermal conductivity [W/(m K)]). Then $F_o$ is the Fourier number defined by $F_o = \alpha H^2$, in which $\alpha$ represents thermal diffusivity [m²/s]. $Q$ and $F_{oh}$ respectively denote the input heat flux per unit time [J/(m²s)] and Fourier number for $t = t_h$ ($F_{oh} = \alpha t_h / H^2$). In Eq. (2), $\mu_n$ is determined from the following relation:

$$\tan(\mu) = \frac{\frac{\mu h}{H} - \left(\frac{h}{k}\right)^2}{\left(\frac{\mu}{H}\right)^2} \quad (3)$$

The Fourier-transformed expression of Eq. (2) is given as

$$F(f) = \frac{2Q}{h} \sum_{n=1}^{\infty} \frac{Bi}{B_i^2 + 2Bi + \mu_n^2} \left(1 - e^{n^2 F_{oh}}\right) \frac{e^{j2nf/\mu_n} e^{j2nf/\mu_n}}{\mu_n^2 \alpha + j2\pi f} \quad (4)$$
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In the calculations, heating duration \( t_h \) was varied under a constant heating rate \( Q \) of 4500 J/(m\(^2\)s).

The phase noise is caused by the temperature noise in \( T(t) \) [6]. The temperature noise follows a normal distribution [4]. Therefore, random numbers with the normal distribution (standard deviation \( \sigma = 0.065 \) °C, experimentally observed values from a previous study [4]) were added as artificial noise to the temperature calculated from Eq. (2) \((H = 20 \text{ mm})\). Then the Fourier transform was applied to obtain the phase data with phase noise. In the calculations, heating duration \( t_h \) was set to 10, 60, and 300 s, and the phase noise amplitude was calculated as a function of frequency for each \( t_h \). Thermal properties and heat transfer coefficient \( h \) used in the calculations were represented in Table 1. The phase noise amplitude was calculated 10 times using different random numbers for each \( t_h \), and was defined as the peak-to-peak value of phase fluctuation.

### Table 1 Thermal properties used in the calculations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho ) [kg/m(^3)]</td>
<td>1190</td>
</tr>
<tr>
<td>Specific heat capacity ( c ) [J/(kg K)]</td>
<td>1470</td>
</tr>
<tr>
<td>Thermal conductivity ( k ) [W/(m K)]</td>
<td>0.19</td>
</tr>
<tr>
<td>Thermal diffusivity ( \alpha ) [mm(^2)/s]</td>
<td>0.109</td>
</tr>
<tr>
<td>Heat transfer coefficient ( h ) [W/(m(^2)K)]</td>
<td>4.7</td>
</tr>
</tbody>
</table>

### 3.2 Experiment for a CFRP specimen

Analytical results were verified by an experiment for a CFRP specimen with artificial defects. In the experiment, Thermo Inspector (KJTD Co. Ltd. [7]) was used. This system contains an infrared camera (SC4000, FLIR Systems Inc.), a heat source (halogen lamp, 1000 W \( \times \) 1), and a PC to construct temperature and phase images. The CFRP specimen reinforced with PAN based carbon fibers (T300, Toray Co. Ltd.) is given in Fig. 3. This specimen has twelve flat-bottomed holes as artificial defects. The depths of the defects from the surface were varied from 0.5 mm to 15 mm, and the diameter of all the defects was 10 mm. The surface of the specimen was heated for 10, 30 and 60 s, and phase images after stop heating were obtained. In addition, phase images after applying instantaneous pulse heating were also obtained for comparison. In the PT inspection, two Xe flash lamps (1000 J \( \times \) 2) were used for heating the specimen instead of the halogen lamp.

![Fig.3 CFRP specimen with flat-bottomed holes as artificial defects.](image)

### 3.3 Results and discussions

#### 3.3.1 Analytical results

Calculated phase noise amplitudes as a function of frequency for \( t_h = 10, 60, 300 \) s are presented in Fig. 4. The phase noise decreases concomitantly with decreasing frequency, and with increasing heating duration. From Eq. (2), surface temperature after long-duration heating with noise is given as

\[
T_n(t) = \frac{2Q}{h} \sum_{n=1}^{\infty} \frac{B_i}{B_i^2 + 2Bi + \mu_n^2} e^{\nu_n^2 F_{oh}^2} e^{\nu_n^2 F_{oh}^2} (1 - e^{\nu_n^2 F_{oh}^2}) + N(t). \tag{5}
\]

Therein, \( N(t) \) denotes the temperature noise. Then, Eq. (5) is Fourier-transformed to

\[
F_n(f) = \frac{2Q}{h} \sum_{n=1}^{\infty} \frac{B_i}{B_i^2 + 2Bi + \mu_n^2} \left(1 - e^{\nu_n^2 F_{oh}^2} \right) \frac{e^{i2\pi f t_h}}{H^2 + j2\pi f} + N(f). \tag{6}
\]

where the transformed noise is given as \( N(f) \). Consequently, phase including phase noise is calculated from
Therein, $R_n(f)$ and $I_n(f)$ are the real and imaginary parts of $N_f(f)$.

The calculated $I(f)$ for $t_h = 10, 60$ and $300$ s and $I_n(f)$ are shown in Fig. 5. Whereas the absolute value of $I(f)$ tends to increase concomitantly with decreasing frequency and increasing $t_h$ as shown in Fig. 5(a), $I_n(f)$ is maintained within a small value irrespective of frequency (Fig.5(b)). $R(f)$ and $R_n(f)$ has the same tendencies with the I(f) and $I_n(f)$. Therefore, $R_n(f)$ and $I_n(f)$ are less influenced to $\phi_n(f)$ at lower frequency especially when $t_h$ is large. This is the reason for decreasing the phase noise with decreasing frequency and with increasing $t_h$ as shown in Fig. 4.

## 3.3.2 Experimental results

Figure 6 shows the experimentally obtained phase noise amplitude as a function of frequency for each heating duration ($t_h$). It is clearly found from this figure that phase noise decreases with increasing heating duration, and that experimental result is consistent with analytical results.

Obtained phase images after pulse and $30$ s heating are presented in Fig. 7. Although the defects up to $5$ mm depth were detected in the image after pulse heating, after $30$ s heating defects up to $7$ mm were detected. These results show applying long-duration heating is effective to improve the detectable defect depth due to reduction of phase noise.

### 3.3.3 Reduction of the influence of ambient temperature fluctuation

The phase noise is expected to be also affected by the fluctuation of ambient temperature (for example, change of room temperature). Therefore,
the influence of $T_f(t)$ was also investigated analytically and experimentally.

4.1 Analytical studies

4.1.1 Calculation setups

Analytical model as shown in Fig.2 (a) was also used. In this study, heat input was assumed as instantaneous pulse heating $Q_p$ [J/m²], and following equation was used to calculate the surface temperature after heating,

$$T(t) = \frac{2Q_p}{\rho c H} \sum_{n=1}^{\infty} \frac{\mu_n^2}{B_n^2 + 2B_n \mu_n^2} e^{-\mu_n^2 t}.$$  \hspace{1cm} (8)

Similar to described in section 3, random numbers with normal distribution ($\sigma = 0.065$ °C) were added to the calculation results as artificial temperature noise. In addition, artificial ambient temperature fluctuation $T_A(t)$ was also added. The $T_f(t)$ was defined by experimentally obtained surface temperature of the specimen without heating. Solid line in Fig.8 shows the measured surface temperature of the specimen, and dashed line in this figure represents 6th order fitting curve. In the calculations, the fitted data was used as $T_f(t)$. The calculated temperature data were Fourier transformed to phase data. The calculations were carried out to obtain phase noise amplitudes with and without $T_f(t)$ under $H = 20$ mm, and the effect of $T_f(t)$ on phase noise was investigated by comparing those results.

In addition, phase data for various depths of defects were also calculated. $H$ was varied from 1 mm to 20 mm, and both with and without $T_f(t)$ were calculated for each $H$. Then phase difference between the result for $H = 20$ mm and those for each $H$ ($\Delta \phi$) were calculated. Assuming the calculation result for $H = 20$ mm is data on non-defective area, results for each $H$ are phase on defect with depth of $H$, and $\Delta \phi$ corresponds with the phase difference between defective and non-defective surface (defect diameter $d$ is infinite). On the basis of this assumption, we investigate the relationship between $\Delta \phi$ and defect depth under both with and without $T_f(t)$. Then, S/N (signal to noise) ratio for each condition was compared.

4.1.2 Results

Figure 9 represents the phase noise amplitude calculated with and without temperature fluctuation $T(t)$. The phase noise with temperature fluctuation are smaller than that without $T_f(t)$ at all frequency. However, the difference is very small (about 1°). These results imply that there is little influence of ambient temperature fluctuation on phase noise.

Figure 10 presents the calculated phase difference under with and without temperature fluctuation $T(t)$ when defect depth $H = 5$ mm. The phase difference obtained from temperature without $T_f(t)$ is larger than that with $T_f(t)$ in low frequency range. Because phase in higher frequency range includes larger noise as seen in Fig.9, using phase data in low frequency range is effective to detect inside defects.
Therefore, the local maximum of the phase difference in low frequency range are defined as $\Delta \phi_p$ (see in Fig.10), and relationship between $\Delta \phi_p$ and defect depth is given in Fig.11. Though the calculations ignore the effect of two-dimensional defect size due to one-dimensional analyses, the phase data is influenced by the defect size, and the $\Delta \phi_p$ should be smaller for defect with smaller diameter $d$. According to previous study [4], relationship between ratio of $\Delta \phi_p$ for $d = 20$ mm to that for $d = \infty$ ($\Delta \phi_p (d = 20) / \Delta \phi_p (d = \infty)$) and defect depth is demonstrated as Fig.12. Dashed line in the figure represents the approximated curve. By using these results, one-dimensionally obtained $\Delta \phi_p$s were transformed to $\Delta \phi_p$ for $d = 20$ mm. In Fig.11, $\Delta \phi_p (d = 20)$ obtained under both with and without $T_f(t)$ are compared. This figure shows that $\Delta \phi_p$ is improved by removing temperature fluctuation at each $H$.

The S/N ratios for each $H$ under $d = 20$ mm are shown in Fig.13. The S/N ratio is also improved by removing the temperature fluctuation at each $H$. This should be due to improvement of $\Delta \phi_p$ as seen in Fig.10.

The calculation results predict that, though the ambient temperature fluctuation has little influence on phase noise amplitude, the S/N ratio is improved by removing it due to enhancement of phase difference. Thus, removing the temperature fluctuation should be effective to enhance the detectable defect depth in the phase images.

4.2 Experiments

4.2.1 Setups

A CFRP specimen used in this study has flat-bottomed holes with $20$ mm in diameter (defect depth $H = 0.5$-$15$ mm), and is reinforced with the same carbon fiber used in the specimen presented in Fig.3. In this experiment, temperature data were obtained by an infrared camera (A315, FLIR Systems Inc.), and two xenon flash lamps (1000 J/F) were used for heating the specimen.
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To control the ambient temperature fluctuation, a temperature control system as shown in Fig.14 was used. This system has a temperature control unit (ORION Machinery Co., LTD.) and a chamber. Temperature in the chamber is controlled in the accuracy of ±1 °C. The specimen was inspected inside and outside the chamber, and the effects due to control the ambient temperature was verified by comparing the results.

4.2.2 Results

Temperatures obtained with and without ambient temperature control are compared in Fig.15. Though the temperature fluctuation was observed as 0.28 °C when the inspection was performed outside the chamber, it was reduced to 0.14 °C when inspecting in the chamber. These results demonstrate that the temperature controlling system works to reduce the influence of ambient temperature fluctuation.

The phase noise amplitudes ($\phi_n$) and the phase difference between defective and non-defective area ($\Delta\phi_p$) under both conditions were also measured. $\phi_n$s obtained with temperature control were almost the same with that without temperature control, similar to seen in Fig.9. On the other hand, the obtained $\Delta\phi_p$s were compared in Fig.16. It is clear that the phase difference is improved by control the ambient temperature, and this tendency corresponds with the results in Fig. 11. Therefore, these results verify the validity of analytical results.

Figure 17 represents the obtained phase images under with and without temperature control. By comparing the images, phase contrast on the defects are enhanced in the image with temperature control (Fig.17 (b)). This should be due to the improvement of the phase difference on the defects, and due to the improvement of S/N ratio.

Fig.13 Signal to noise ratio calculated with and without temperature fluctuation $T_f(t)$ under defect diameter $d = 10$ mm (calculated using the results presented in Fig.12).

Fig.14 Temperature control system.
5 Conclusions

To improve the detectable defect depth by pulse phase thermography, we focused on the noise appears in phase images, and two method to decrease the phase noise were examined. The main findings in this study are as follows:

1) Phase noise is decreased with increasing heating duration. This is due to the increase of input heat.

2) There is little influence of the ambient temperature fluctuation on phase noise amplitude.

3) The phase difference between defective and non-defective area is improved by removing the ambient temperature fluctuation.

Experimental results demonstrate that, though detectable defect depth by instantaneous pulse heating was up to about 5 mm, that by 30 s heating was improved up to 7 mm. This is due to the decreasing of phase noise, and due to improvement of S/N ratio. Analytical results demonstrate that lower phase noise is achieved by longer heating duration. However, maximum surface temperature is also increased with increasing heating duration (in our experiments, the surface temperature reached about 100 °C after applying 60 s heating). Therefore, applicable heating duration depends on temperature limit of the tested materials not to damage them thermally.

Though ambient temperature fluctuation is independent of the phase noise, it was additionally found that removing the fluctuation lead to improvement of the phase difference between defective and non-defective area. This results in the enhancement of detectable defect depth.

References


