NDE of the Internal Defect of PVC Pipe using Infrared Lock-in Thermography

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Abstract
The purpose of this study was to detect the internal defect of PVC pipe using lock-in thermography method. Amplitude and phase images of the pipe specimens were analyzed according to the lock-in frequency and the diameter of defect area. The phase image analysis, for defect diameters 2 mm above and thickness 2 mm below, exhibited the highest phase contrast value between defective area and sound area. The lock-in frequency range of 0.25-0.05 Hz provided good phase angle contrast for the defect area. It is concluded that the infrared lock-in thermography method verified the effectiveness for detecting the internal hole defect of PVC pipe.

Keywords: Lock-in Thermography, PVC pipe, Internal defect, Phase image

1. Introduction

PVC and CPVC pipes and fittings are excellent products and have been used successfully for decades. PVC and CPVC pipes are one of the most extensively used plastic piping materials. The main reason for the great success of these pipes is their low cost, extremely low failure rate, and relative ease of installation. However, as with all piping materials, there are occasional failures. These unexpected piping failures in the factory may influence employee health. Therefore, periodic inspection of the internal pipe is important.

Internal defect of pipes has been analyzed by radiographic test (RT), ultrasonic test (UT) and acoustic emission (AE) [1, 2]. Ultrasonic test is less applies to non-metallic piping and acoustic emission is a dynamic test method for the signal detection during the flaw progress. Radiographic test is available to detect internal defects of the non-metallic pipe. However, the risk of radiation exposure, it is difficult to satisfy the safety regulations of company.

Lock-in thermography utilizes an infrared camera to detect the surface temperature of a thermal wave propagating into the material and then produces phase or amplitude images[8,9]. Lock-in thermography can be used to detect subsurface defects through the differences in phase or amplitude. Lock-in thermography has two main advantages in comparison to steady-state thermography: an improved signal-to-noise ratio and a better spatial resolution. In the low sampling, because this method can sense the minute change of the surface, defect and failure detection are possible in the small phase change. The phase change image has the advantage that the error by the non-uniformity of the object surface emissivity is small [3, 4].

In this study, digital lock-in correlation method was exploited to calculate amplitude and phase images about subsurface defects. The PVC pipe specimen with flat bottomed hole defects of various depths and diameters was made. The purpose of this study is to investigate the feasibility on detection of a defect in nonmetal pipe using the lock-in infrared thermography.
2. Digital Lock-in Correlation Method

Figure 1(a) shows the principle of the digital lock-in correlation procedure. Lock-in thermography makes use of periodic optical stimulation to heat the sample, using sinusoidally modulated halogen lamps [5, 6]. The term lock-in refers to the monitoring of the exact time difference between the output signal and the reference input signal. Hence, amplitude and phase images of the reconstructed thermal wave can be computed for each heat-generating frequency by post-processing the recorded image data using the Fourier transform algorithm. The signal detected from the basis function can be shown as follows:

\[
S = \frac{1}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} K_j F_{i,j} \tag{1}
\]

where, \( F_{i,j} \) denotes the temperature measurement at the time of the \( j \)-th frame in the \( i \)-th lock-in period. The weighting factors \( K_j \) are given by

\[
K_j^0 = 2 \sin \left( \frac{2\pi(j-1)}{n} \right) \tag{2}
\]

\[
K_j^{90} = 2 \cos \left( \frac{2\pi(j-1)}{n} \right) \tag{3}
\]

The amplitude \( A \) and the signal phase \( \Phi \) can easily be retrieved from the two results \( S^0 \) and \( S^{90} \). Then, the amplitude (A) and the phase (\( \Phi \)) are:

\[
A = \sqrt{(S^0)^2 + (S^{90})^2} \tag{4}
\]

\[
\Phi = \arctan \left( \frac{S^{90}}{S^0} \right) \tag{5}
\]

![Figure 1. Principal of the digital Lock-in thermography correlation procedure (a) and complex vector representation of the amplitude and phase relations in the two channel lock-in process (b) [7]]
3. Experimental

3.1 Specimen preparation

Wall thinning with chemical reactions is one of the common defects in piping systems. To investigate the detectivity of lock-in thermography, it is necessary to make a calibration specimen which contains expected defects of various sizes and at various depths. Specimens were prepared as shown in Figure 2. PVC pipe (80A, diameter 80 mm) divided into two parts was prepared. A tungsten carbide end-mill tool of 1, 2 and 3 mm in diameter (YG, 3S MILLS, Korea) driven at a high rotation speed and a very low feeding speed, under a air spray, was used to make the internal hole. Defects with these diameters were inserted at each of the following depths below the surface: 1, 1.5, 2 and 3 mm.

![Figure 2. Schematic of PVC pipe specimen containing various holes](image)

Figure 2. Schematic of PVC pipe specimen containing various holes

3.2 Set-up for Lock-in infrared thermography

Fig. 3 shows a schematic of experimental set-up for lock-in infrared thermography used in this study. For generation of sine waves of a single frequency, a programmable software (DisplayIMG) and a controller (OTvis, Edvis, Germany) were used. The outer surface of the
specimens was heated with a modulated heat wave from the 2.5 kW halogen lamp kept approximately 50 cm away from the specimen. The heat source was driven by the lock-in module which was controlled by DisplayIMG software. The heat source and the infrared camera signals were synchronized. The surface temperature field was measured with a radiometric infrared camera (655SC, FLIR, Germany) equipped with a 640×480 pixels detector. The spatial resolution of the camera was 0.68 mrad and a thermal sensitivity was 30 mK. Experimental conditions were lock-in period of 3 times and a camera frame rate of 50 Hz. Lock-in frequency range was 0.01-0.5 Hz. All measurements were performed at room temperature.

4. Results and discussion

Since the lock-in thermography uses the same heat source of the halogen lamp, the surface temperature of the holed region in accordance with the lessened pipe thickness is to be higher than the sound area. The amplitude and phase contrast in the thermal images is generated by this surface temperature difference. As shown in Figure 4, amplitude and phase image showed some differences in detection images according to the lock-in frequency and hole size. At frequency range 0.025-0.05 Hz, a clear contrast of the hole image was shown. At a lock-on frequency of 0.01 Hz, the halogen lamp has long light-on duration at the same pulse-duty. Thus it irradiated a large heat quantity in specimen where the specimen surface heat was saturated to lessen the contrast difference of the amplitude. On the contrary at 0.3 Hz and higher frequencies, the heat was insufficiently supplied in the specimen so that the temperature differential at the hole and sound region influenced by the heat conduction was small. It is because good heat-conduction in the soundness part led to a decrease in the contrast as compared with that of the holed region. As to the hole diameter of 1 mm, detection was impossible at the present lock-in frequencies.

![Figure 4. Amplitude and Phase images of holed specimens at various frequencies and hole diameters](image)

The contrast difference between the sound and the holed regions can be given by the equation,

$$\text{Contrast ratio, } C = \frac{P_d - P_s}{P_s}$$  \hspace{1cm} (6)

Here, $P_d$ is calculated with the average phase of the hole image pixels including boundary data. $P_s$ is the average of pixel data for the sound part.
Fig. 6 shows the phase contrast difference of 3 mm diameter holes as a function of the lock-in frequency. The frequency range in which the hole image was distinctive similar to the visual image was 0.025-0.1 Hz. Through the phase image, the small pipe hole thickness of 1 mm caused large contrast ratios at 0.5 Hz and 0.1 Hz. Hole thickness 1.5 mm gave quite large contrasts at 0.025 and 0.05 Hz (Figure 5). With decreasing the frequency below the critical value, the phase difference was enlarged in the negative due to the heat saturation of the specimen surface.

Signal-to-noise ratio (SNR) was calculated by the absolute value of the difference between the phase averages in the holed and the sound region, divided by the standard deviation ($\sigma_s$) of the sound region data [8]

$$SNR = \frac{|P_d - P_s|}{\sigma_s}$$  

(7)

The SNR may offer a quantified detectable thermal image. SNR results as a function of lock-in frequency were plotted in Figure 6. The SNR value was relatively high at 0.05 Hz, which was similarly observed in the contrast ratio result. For the hole thickness 1 mm and 1.5 mm, SNR value was high at 0.05 Hz, where contrast ratio was also high. The contrast ratio and SNR increased as the hole thickness decreased.
5. Conclusions

In this study, artificial hole defects in PVC pipe are detected using a lock-in thermography method. Amplitude and phase images of the specimens were analyzed according to the lock-in frequency and the thickness of holes. The infrared lock-in thermography method showed the effective optimum condition for detecting the hole in PVC pipe.

References