[Original paper]
Journal of the Korean Society for Nondestructive Testing
Vol. 32, No. 3 (2012. 6)

A Study on the Optimized Test Condition of Lock-in IR Thermography by Image Processing

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Abstract In this study, it was studies the utilization of LIT(lock-in infrared thermography) which can detect defects in welded parts of ship and offshore structures. Quantitative analysis was used through methods of filtering and texture measurement of image processing techniques to find the optimized experimental condition. We verified reliability in our methods by applying image processing techniques in order to normalize evaluations of comparative images that show phase difference. In addition, low to mid exposure showed good results whereas high exposure did not provide significant results in regards to intensity of light exposure on surface. Lock-in frequency was satisfactory around 0.1 Hz regardless of intensity of light source we had. In addition, having the integration time of thermography camera inversely proportional to intensity of exposed light source during the experiment allowed good outcome of results.

Keywords: Texture Measurement, Design of Experiments, Optical Intensity, Lock-in Frequency, Integration Time

1. Introduction

Infrared is a name given to electromagnetic waves with wavelengths longer than the ones of visible rays but shorter than the ones of microwaves which is not visible to our eyes but possesses properties with strong thermal effects as shown in Fig. 1. This is because according to Stefan-Boltzmann's Law, infrared energy emitted from matter is proportional to the fourth power of absolute temperature of the matter. However, infrared has short effective distance because it is scattered and absorbed by moisture and carbon dioxide since infrared is similar to unique oscillation frequency of atmospheric matters. Its usage has been restricted until recently since development of its detector has been difficult due to low wave band.

Recently, development of infrared sensors has become more active and less costly so it has begun to be applied in many fields thanks to breakthrough development in semiconductor production technology.

For commercial usage, temperature difference of steady-state is imaged so such utilization is referred to as traditional steady-state thermography [1,2].

Moreover, LIT which utilizes active optical excitation is known to be unaffected by noise such as reflections from surrounding environment.

Accordingly, satisfying nondestructive defect detection can be expected by applying LIT in

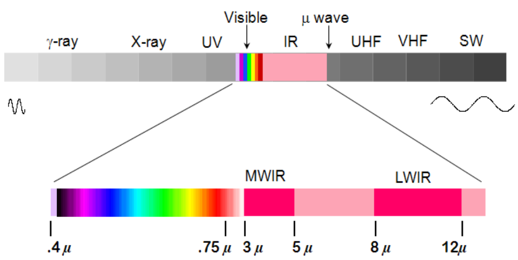

Fig. 1 Infrared in the electromagnetic spectrum

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shipbuilding and marine engineering industries where it is complex with many environmental noises.

In this study optimized experimental condition for utilization of LIT technique which can detect defects in welded parts of Ship and Offshore structures was examined.

For methods of experiment, 3 types of factors were selected which are capable of control according to experiments design by using previously developed standard test specimen and also characteristic value (dependent variable) was quantitatively analyzed through image filtering and texture inspection methods of image processing technique [3-5].

2. Lock-in Infrared Thermography Technique

LIT technique which uses dynamic thermography is a method for observing changes to phase, amplification and more by processing response signal of target object upon emission of stimulant on to the target object in harmonic function.

Equation (1) express 1-dimensional heat trans- fer equation within solids. Here, T stands for temperature, t for time, k for coefficient of thermal conductivity, ρ for density, c_p for specific heat and x for direction of thermal flow. When optical excitation by halogen lamp becomes the external stimulant in harmonic function($T=T_o coswt$), LIT method could derect the inside defects of solids presented by observing changes to heat source that diffused into target object [1, 6-8].

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial x^2} \quad (1)$$

Solution for equation (1) that is heated with harmonic function maybe expressed as equation (2).

$$T(x,t) = T_0 e^{-x/\mu}\cos(wt - x/\mu) \quad (2)$$

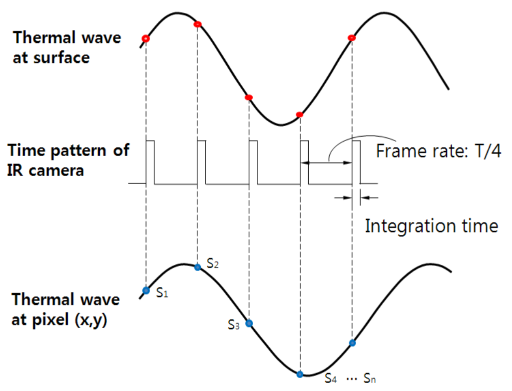


Fig. 2 Principle of lock-in thermography

Here, $\mu = \sqrt{\alpha/\pi f}$ signifies thermal diffusion length and $\alpha = k/\rho C_p$ signifies thermal diffusivity.

Surface of defective area inside the object would produce different phase compared to normal region without defects. Lock-in system and software allows us to identify the faulty area by calculating changes in amplification and phases.

Such thermography presents changes in thermal waves according to locations as amplification and phases. Fig. 2 shows principles behind lock-in thermography technique.

After a few modulation periods, average of at least 4 images is obtained for every cycle. However, all images are in the end merged together into basic images (S_1, S_2, S_3 and S_4) due to sine wave modulation.

$$A(x,y) = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2} \quad (3)$$

$$\phi(x_1) = \tan^{-1}\left(\frac{S_3 - S_1}{S_4 - S_2}\right) \quad (4)$$

Subsequently, phase angle and amplification value of these merged images are obtained from equation (3) and (4) above. Because equation above calculates the differences between (S_1 and S_3) and (S_2 and S_4), effects of noise due to uneven emission of optical excitation in Lock-in, surface emissivity and reflection due to surrounding environment can be rejected [5].

3. Research Method

3.1 Designing Experiment Factors

For study method, multi-way factorial design which is capable of investigating wide range of factors was used. Optimization process was conducted by quantification through image processing of comparative images that show phase difference between normal and defective areas according to test conditions [9].

First, controllable experimental factors for variables that could influence characteristic values of LIT were selected. Also, uncontrollable or unaffecting variables as noise were considered. Table 1 shows such selected input test factors.

Selected factors (variables) underwent wide modeling in order to be able to search areas as wide as possible. First, aluminum alloy and carbon steel were used as test specimens, which are widely used in shipbuilding and marine engineering fields. The level of light amplification oscillation was determined through analog adjustment.

Table 1 Design factors and noise factors

	Parameters
Design factors	- Material of specimen - Optical Intensity - Lock-in Frequency - Camera's Integration Time
Noise factors	- Non-homogeneous illumination - Surface emissivity - Ambient radiation - Air Temperature - Relative Humidity - CO_2 gases partial pressure - Wind seed/direction - Movement of persons

Levels of factors were determined as 30%(Q3), 50%(Q5) and 70%(Q7) by applying linear proportion to maximum oscillation (1 kW). In addition, the experiment was performed by setting fine intervals for lock-in frequency from 0.01 Hz to 1.0 Hz [4].

For integrated time of camera, levels determined were 400 μs(open), 180 μs(open) and 280 μs(w/filter) depending of specifications of infrared camera.

3.2 Configuration of Experiment Devices

The Fig. 3 is shows the system of LIT measuring devices by appropriately combining series of equipments.

Lock-in Infrared Thermography detecting device through light amplification oscillating device of halogen lamp is comprised of light emitting equipment, lock-in control device, thermography camera and test specimen [6,7].

For safe conduct, test equipments were set up on aluminum plate color coated in black and effects of disturbances were tried to be minimized by performing the experiment in cleanly closed laboratory.

For heat source of LIT technique, we used 2 halogen lamps (1 kW×2ea) and study results showed that intensity of heat source was sufficient.

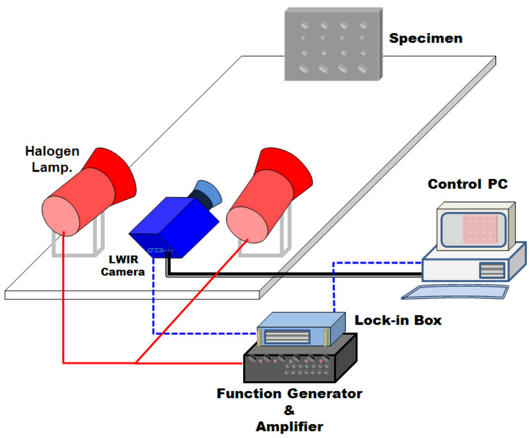
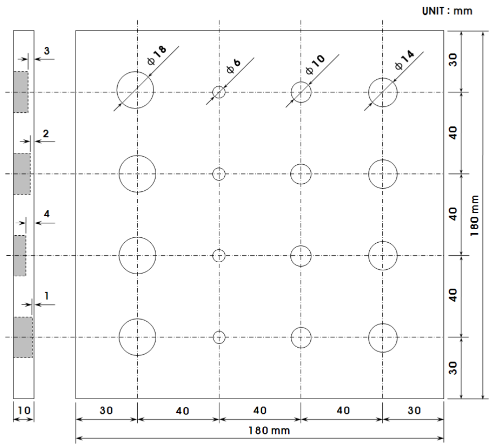
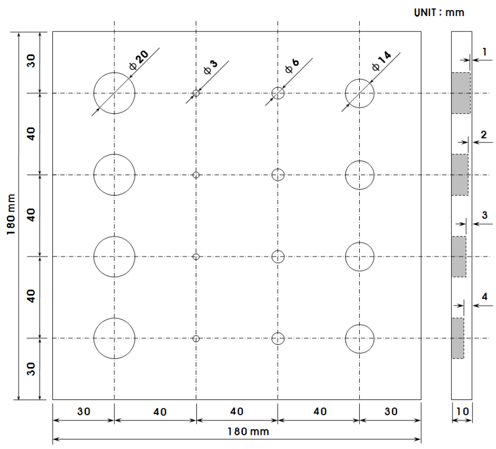


Fig. 3 System configuration of lock-in thermography



(a) Al6061-T6



(b) SM45C

Fig. 4 Specimens with in-planted defects

For infrared camera, far-infrared MCT FPA infrared camera was used, which has best performance with regards to heat resolution in shortest integration time [1].

Accordingly, cooling type equipment of extremely low temperature (JADE LWIR MCT Camera and related sub-parts) was used for infrared camera, which is the core equipment in configuration of LIT system.

Lastly, aluminum alloy and carbon steel standard test pieces were used as specimens, which are widely used in mechanical fields including shipbuilding and marine technology fields in general as well.

Aluminum alloy (Al6061-T6) defective test specimen was used in the experiment by applying standard test piece which has been designed for defect detection through having holes drilled into the back of 180 mm square test piece as shown in Fig. 4(a). Carbon steel (SM45C) defective test specimen as well had holes drilled in the back of standard 180 mm square test piece as shown in Fig. 4(b).

Both test specimens were painted with black colored paint and varnish to increase heat radiation rate.

3.3 Characteristic Value (Dependent Variable)

Exploratory research is a process of quantification to quantitatively judge images that shown phase difference between faulty and normal areas, which are characteristic values depending on changes in levels of experimental factors.

In order to analyze the difference of phase angles between normal and faulty areas, it would be best to quantitatively judge by utilizing comparative images obtained from test results but there is currently no software developed in the country for judgment making.

Furthermore in this research, we developed the following algorithm to allow quantization of images through image processing by using MATLAB program as shown in Fig. 5.

First, adaptive median filter that is not only effective in noise rejection but also allows preservation of edges in original source signals in more detail was used in order to remove localized noises.

For quantization of comparative images of phase difference, we used the method of quantifying texture data through image processing. There exists statistical, structural and spectral methods used in image processing for describing regional texture and statistical approach which is based on statistical

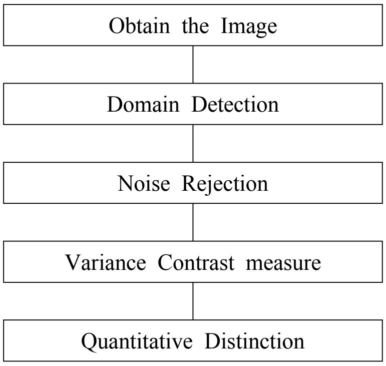


Fig. 5 Algorism scheme of Image processing

characteristics of histograms of images or regional brightness was used for this study.

One of major methods in stating the shape of histogram is about central moments as defined in equation (5) below and expression of n^{th} moment regarding the mean is as follows.

$$\mu_n = \sum_{i=0}^{L-1} (z_i - m)^n p(z_i) \quad (5)$$

Here, z_i stands for random variable expressing brightness, p(z) for histogram of regional brightness level, L for possible number of brightness levels, and m for average value(average brightness) of z. We assume that histogram is normalized so the summation of all components equals to 1. Following onwards from equation (5), $\mu_0 = 1$ and $\mu_1 = 0$. Second moment dispersion $[\sigma^2(z) = \mu^2(z)]$is especially important in texture description.

$$\mu_2 = \sum_{i=0}^{L-1} (z_i - m)^2 p(z_i) \quad (6)$$

Equation (6) pertains to variance. This is a scale for brightness contrast which can be used for deciding descriptors of relative softness.

If the contrast of defective area from comparative images that show phase difference is great, quantification would be made possible due to increased dispersion of histogram.

4. Test Results and Analysis

We conducted optimized experimenting process through multi-way factorial design where in experiment is performed by varying intensity of light amplification, lock-in frequency and camera integration time depending on type of test specimen, which is a design factor. Through such methods, we planned for searching the optimized experimental conditions which show satisfactory characteristic values (phase comparative images).

For study results, results that used reference table which divided comparative images into 6 stages were compared to allow judgment by naked eyes with quantified results that had undergone image processing[10].

Fig. 6 below shows an important example of characteristic value (phase comparative image) according to heat source changes of aluminum test specimen and changes in lock-in frequency. Phase difference comparative images show much difference even due to changes in two factors which are intensity of light emission and lock-in frequency as well.

In Fig. 7, results of quantified characteristic values of aluminum test specimen are presented as bar graph to allow easier comparison according to experimental factors. Whereas the ones explored using standard table are presented as line graph.

Analysis results of experiment showed that best characteristic value resulted from mid (Q5) intensity of light emission that has visibility with regards to intensity of oscillation of light source.

For lock-in frequency, frequency between 0.02 Hz and 0.1 Hz produced good results for low (Q3) light emission whereas frequency between 0.07 Hz and 0.1 Hz had good outcome for mid intensity (Q5) light emission.

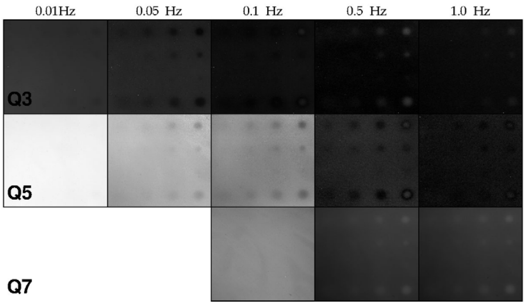


Fig. 6 Phase images of defects test (Al6061 specimen)

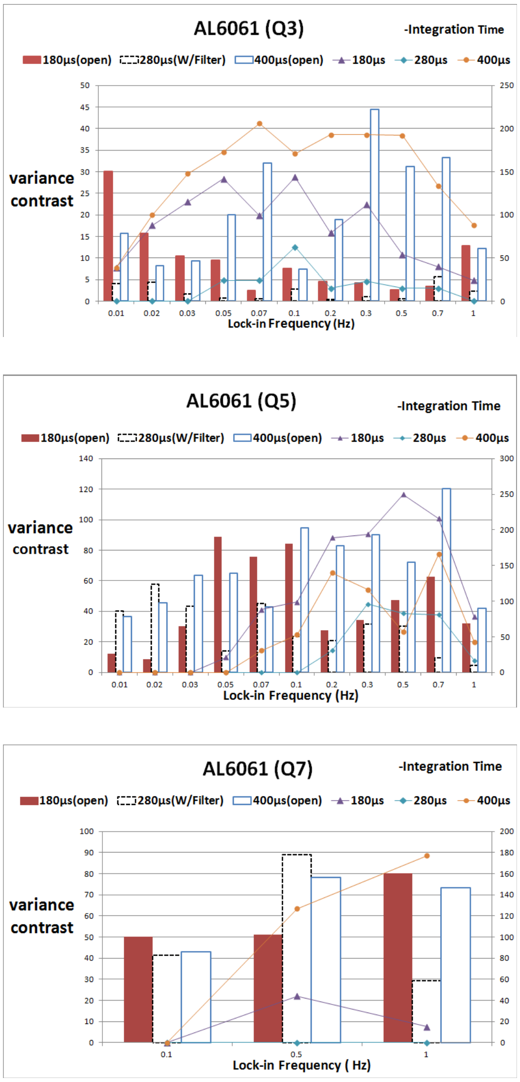


Fig. 7 Analysis results of specimen (Al6061)

For high (Q7) light emission, too much heat emitted upon specimen made defect detection impossible due to easy saturation of surface. This experiment was omitted for low lock-in frequencies because specimen easily reached high temperatures which needed surface cooling by force or waiting time to reach room temperature that in turn decreased accuracy of the experiment.

In experiment using aluminum specimens, results showed similar tendencies as experiment using standard table.

Fig. 8 below shows important example of characteristic value of carbon steel specimen according to changes in light source intensity and lock-infrequency.

As shown in Fig. 9, Based on analysis of results from carbon steel specimen, results showed similar tendencies to aluminum but difference in characteristic values and slight biased results were present. Results around 0.1 Hz for low (Q3) light source oscillating intensity produced good results but with relatively low characteristic values whereas mid (Q5) light emission showed satisfactory results around 0.07 Hz.

At high (Q7) light emission, surface became easily saturated as with aluminum specimen so defect detection was impossible. Accordingly, due to difficulty with experimentation as with aluminum specimen, experimentation in low lock-in frequencies were omitted.

For carbon steel specimen, there was difference with investigation using reference table in regards to bias but in the end presented similar results.

Regarding integration time factor of infrared camera, attaching filter for detection of high temperature produced bad results in all conditions.

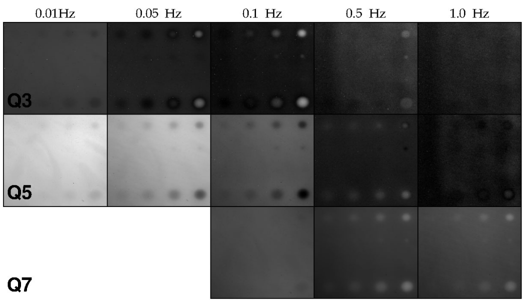


Fig. 8 Phase images of defects test (SM45C specimen)

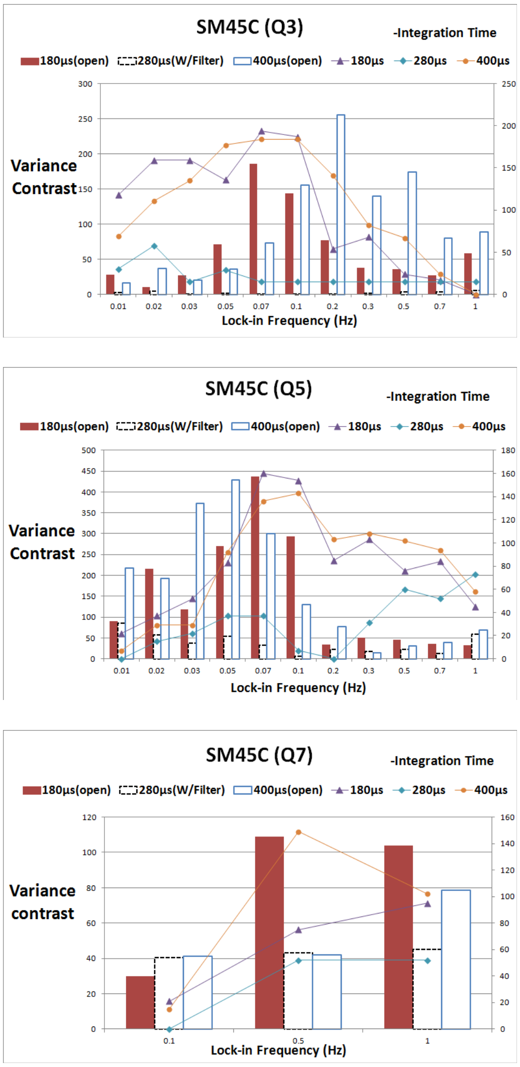


Fig. 9 Analysis results of specimen (SM45C)

For changing integration time without filter, there was correlation with light emission intensity for aluminum specimen. In other words, at mid (Q5) light emission, it is better to reduce integration time of infrared camera where as conversely increasing the integration time for low (Q3) light emission would improve the outcome of results. However, analysis results for carbon steel specimen did not clearly show correlation. Lastly, for difference between two specimens with different thermal physical properties of conductivity, we confirmed that aluminum specimen that has high heat conductivity produced satisfactory results in biased band at a little lower frequency with regards to frequency that produces optimized characteristic values.

However, for relationship with light emission intensity, reciprocal interaction occurred in two specimens so significant results could not be obtained.

5. Conclusion

In order to obtain optimized phase comparative images of defective regions through lock-in infrared thermography, we selected test factors and conducted exploratory research according to experiments design in coming up with the following conclusion.

(1) Method of quantifying phase difference images of defective and normal areas into characteristic values by using newly developed algorithm can be a reliable method for exploratory research in finding optimized conditions.

(2) For intensity of light emission, low (Q3) or mid (Q5) light amplified emission produced relatively better results whereas high light emission did not due to reaching state of heat saturation.

(3) For optimized lock-in frequency, satisfactory phase comparative images were obtained around 0.1 Hz regardless of intensity of light source.
(4) Good results cannot be expected from using filter of thermography camera but they can be obtained by performing the experiment with integrated time inversely proportional to intensity of emitted light source.
(5) Lastly, characteristic value according to thermal physical properties of specimen should slight biased results depending of frequency.

Study results above produced satisfactory results by developing method of quantification through image processing in order to obtain optimized experimental conditions of Lock-in Infrared Thermography technique. It is planned to conduct additional researches for increasing reproducibility and precision of optimized experimental conditions through statistical analysis in the future.

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