LOCK-IN THERMOGRAPHY IMAGE PROCESING

Petra, **BAGAVAC**, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, CROATIA, Phone: +38521305626
petra.bagavac@fesb.hr

ABSTRACT *- Composite materials have appropriate thermal properties for detection flaws by means of non-destructive infrared thermography methods. Infrared thermography methods are based on tracking heat flow that has been induced by flood lamps. Lock-in thermography, as one of infrared thermography methods, is used in detection of flaws. Surface of specimen is periodically heated by heat flow in form of sinusoid. Presented method enables reconstruction of sinusoid wave after reflection from defect boundaries. Parameters of reconstructed heat wave differ for waves reflected from non-damaged and damaged material. The period of excitation is varied. In the presented article a basic theory of lock-in thermography and signal processing is given. The lock-in method is applied on samples made of carbon fibers reinforced plastic in order to show possibilities of developed method.*

Keywords: *composite materials, non-destructive testing, lock-in thermography*

OBRADA TERMOGRAFA LOCK-IN METODOM

SAŽETAK *– Kompozitni materijali, zbog svoje relativno male toplinske vodljivosti u usporedbi s metalima, omogućavaju primjenu infracrvene termografije kao metode bez razaranja temeljene na ostvarivanju toplinskog toka putem halogenih reflektora. Toplinski val prodire u kompozitni materijal i širi se unutar materijala odbijajući se o granice grešaka. Ova metoda prati odziv materijala, tako što se snima raspodjela temperatura na površini uzorka infracrvenom dugovalnom kamerom. Iz prikupljene sekvence termograma, pomoću lock-in metode, rekonstruira se toplinski val. Uspoređuju se razlike u parametrima toplinskog vala koji je prošao samo kroz zdrav materijal i vala koji je prošao kroz oštećen materijal. U ovom radu se varira dužina trajanja perioda uzbudne sinusoidne funkcije kako bi se otkrile greške na različitim dubinama u ispitivanom uzorku. U radu su opisani temelji primjene lock-in termografije. Na primjerima su prikazane mogućnosti metode pri detekciji oštećenja kod polimernih kompozita ojačanih karbonskim vlaknima.*

Ključne riječi: *detekcija oštećenja metodama bez razaranja, kompozitni materijali, lock-in termografija*

1. INTRODUCTION

Composite materials offer an important alternative to metallic materials because of their high stiffness and weight ratio. In last few decades, composite materials, primarily CFRP, are broadly used in aeronautical and car industry, reducing structure weight up to 50%. During the manufacturing process and later in exploitation, parts of a vehicle experience damages. It is preferable to detect these damages as soon as possible in order to be able to make appropriate choices such as repair, reinforcement of standard replacement of damaged parts. Variability of the composites behaviour limits their development and require fast end precise non-destructive testing techniques. Infrared thermography is established as a good option. IR thermography can be divided into two approaches, the passive and active thermography. The passive thermography tests materials and structures which are naturally at different temperature than ambient [1-3] while in the case of active thermography, an external stimulus is necessary to induce relevant thermal contrast. Depending on the external stimulus, different methods of active thermography have been developed: phase thermography (PT), lock-in thermography (LT), pulse phase thermography (PPT) and vibrothermography (VT). The lock-in thermography is a method of active thermography used for non-destructive testing of materials. The surface of a specimen is periodically heated by modulated flood lamps [4-6]. The lock-in thermography refers to the necessity to monitor the exact time dependence between the output signal and the reference input signal. The resulting oscillating temperature field in the stationary regime is remotely recorded through its thermal IR emission [7]. Excitation is defined by the magnitude and period of modulated heat, Q and P respectively, and is similar to sinusoid heat wave. Depending on thermal properties, thickness and expected depth of the material being inspected the heating period can variate from few to few hundred seconds [5, 7].

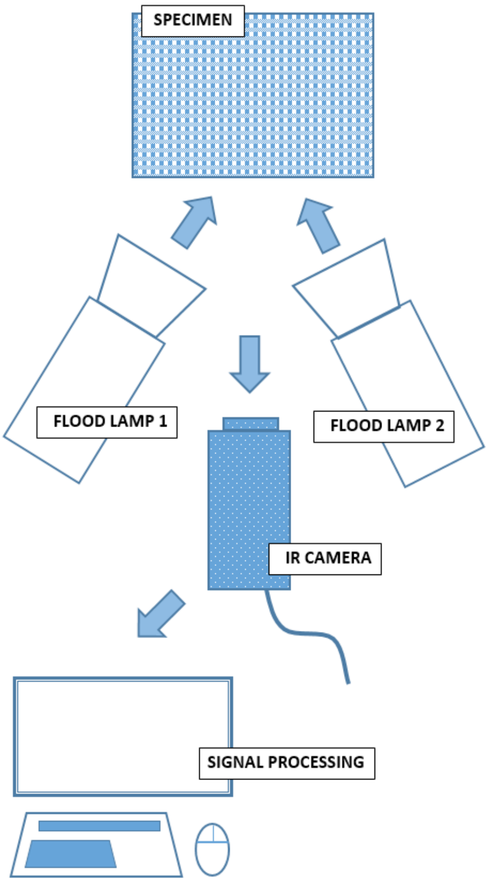

Figure 1 *Schematic configuration for LT, [8]*

Once the heat flow reaches the specimen, the thermal wave propagates trough the material and reflects from the boundaries of specimen or from damaged area causing signal response of specimen. A schematic configuration for LT is shown in ***Figure 1.***

Reflected thermal waves are determined by the amplitude, phase and angular frequency $[A_{tw}, \phi_{tw}, \omega]$. The principle of the damage detection is based on the fact that damaged zones will have phase delay with regard to non-damaged zones, as shown in ***Figure 2.*** This phase delay is consequence of different thermal properties of damaged and non-damaged material [4-6, 9-11]. Flaws in composite materials can be cracks or delamination, and if so, the substance of damage is air, or for the case osmotic blister, water or glycol.

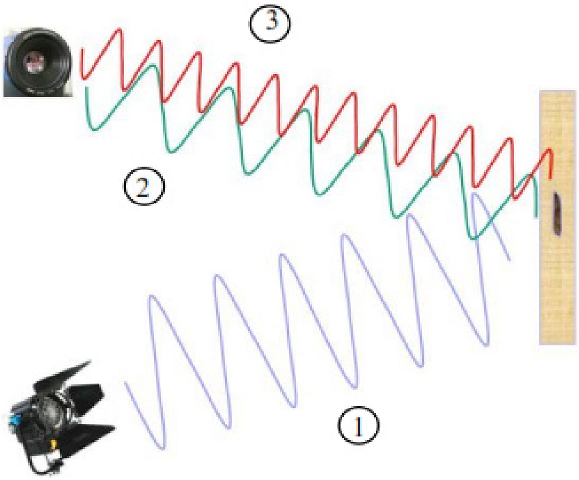

Figure 2 *Sinusoidal excitation wave and wave rensponse, [4]*

The reconstruction of sinusoid thermal wave is possible from the data acquired by thermal camera, as shown in ***Figure 3.*** In the presented approach, four thermal images are

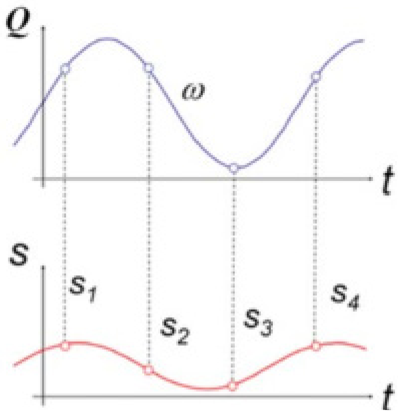

Figure 3 *Amplitude and phase retrieval from a sinusoidal thermal excitation, [4]*

used for signal processing, resulting in only one amplitude image and one phase image.

For each specific pixel on four different, but equally time spaced thermal images, temperature data (S_1, S_2, S_3, S_4) are used to calculate amplitude and phase [11, 12].

$$A_{tw}(x,y) = \sqrt{[S_1(x,y) - S_3(x,y)]^2 + [S_2(x,y) - S_4(x,y)]^2} \quad (1)$$

$$\phi_{tw}(x,y) = \arctan\frac{S_1(x,y) - S_3(x,y)}{S_2(x,y) - S_4(x,y)} \quad (2)$$

Each of used thermal images is spaced for ¼ period of excitation. As follows from the above, the shortest time of heating is equal to one period of excitation. In a practice, the specimen is heated at least one and a half period of excitation.

After the signal processing is done, defects are revealed in more distinguishable way. One of the main reasons for better detection of damaged areas is that the phase images are less affected by non-uniform heating, surface emissivity variations or environment reflections, than raw thermal images [4, 5, 13, 14]. The Excitation frequency of the thermal wave is directly correlated with the phase delay. To generate enough visible phase delay, excitation frequency must be chosen correctly [5, 10], i.e. deeper damages can be detected if lower excitation frequency is used, while shallow damages can be detected if higher excitation frequency is used.

2. THE THERMAL AQUISITION

The Test specimen is made from the carbon fibres reinforced plastic. The Specimen is deliberately damaged with the controlled metal rod impact. The metal rod was released from the height of 2 m on the surface of specimen, handing over 19.62 J of impact energy. The damaged specimen is examined by the Lock-in method. Damaged surface of specimen is rotated against infrared camera. Three consequent measurements of exposed specimen are taken, where the period of excitation is varied. The parameters of acquisition are given in ***Table 1.***

Table 1 *Heating period, modulation freq., recording time, sampling freq. and number of thermal images taken*

Heating period	Modulation freq.	Recording time	Sampling freq.	Num of therm.
24 s	0.0417 Hz	36 s	1 Hz	36
72 s	0.0139 Hz	108 s	0.5 Hz	54
120 s	0.0083 Hz	180s	0.5 Hz	90

The Surface of the specimen is heated by two 0.5 kW pulse modulated flood lamps submitting it to a periodic thermal stimulation. Experimental setup is shown in ***Figure 4*** and heating of the specimen is shown in ***Figure 5.*** The lock-in thermography refers to the necessity to monitor the exact time dependence between the output signal and the reference input signal.

The output signal (thermografic sequence) is acquired by the cooled middle wave infrared camera FLIR SC 5000, with 320x256 pixel resolution, 0.02 K sensitivity, and 150 Hz acquisition frequency [15].

Figure 4 *Experimental setup*

Figure 5 *The thermal aquisition*

3. RESULTS

Influences such as uneven heating (visible in raw thermal image, ***Figure 6***), environment reflection and surface coating are contaminating thermal image, making the detection of damages hardly visible. On the raw thermal image, the direction of carbon fibres is partially visible. Inclusions of air contained in damaged zone are not detectable on the raw thermal image. Four of thermal images are used for signal processing from every of three thermogram sequences acquired by the infrared camera. The signal processing is carried out by Matlab R2010b. Processing time was of the order of few minutes.

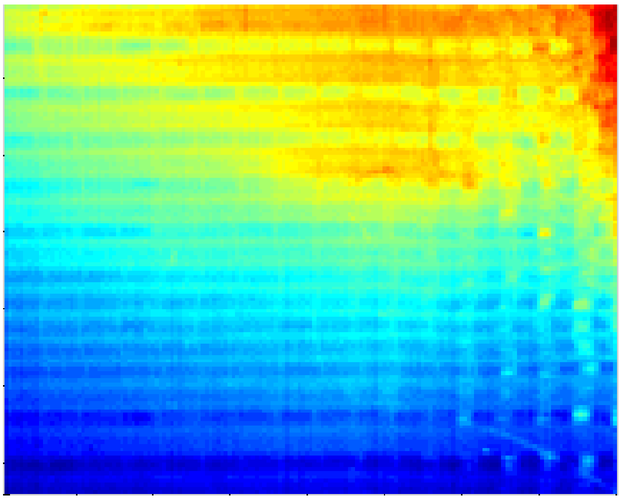

Figure 6 *The raw thermal image*

On the phase image in ***Figure 7*** modulating period is the shortest one (P=24 s), what corresponds to the highest modulation frequency, revealing damages near the surface. Revealed damages are mostly air inclusions remained the from production process, while the damage made by impactor is not visible.

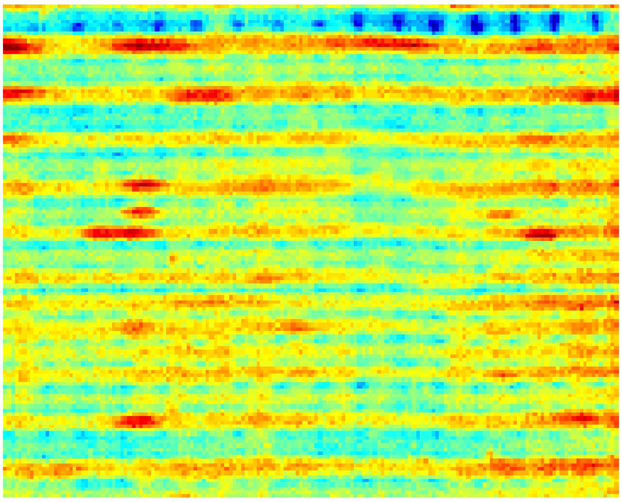

Figure 7 *TThe phase image for the period P=24 s*

On the phase image in ***Figure 8*** modulating period is P=72 s, what corresponds to the middle range frequency. The heat wave has enough energy to penetrate inside the material, revealing the crack made by the impactor. On the other hand, the air inclusions are less visible because the heat wave has enough energy to penetrate the surrounding material up to the same level.

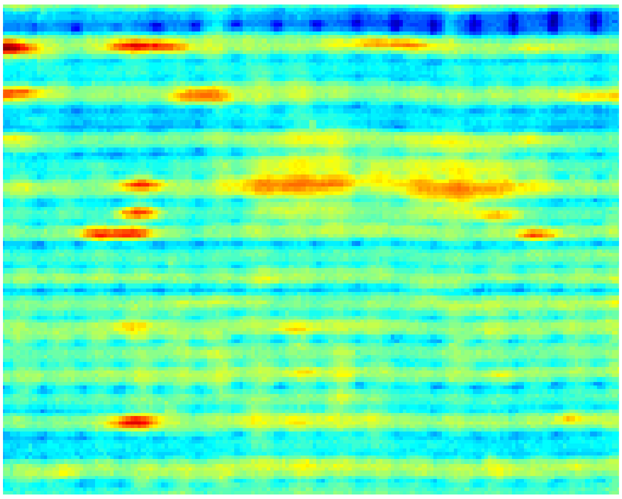

Figure 8 *The phase image for the period P=72 s*

On the phase image in ***Figure 9***, modulating period is P=120s, what corresponds to the lowest frequency. The heat wave has high energy and penetrates deep inside the material, making the damage clearly visible.

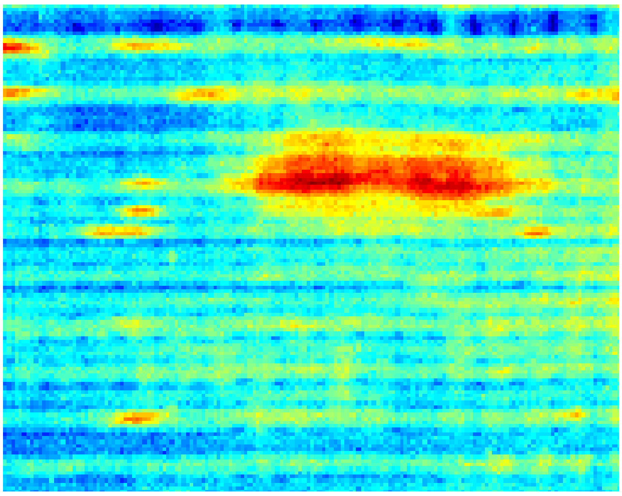

Figure 9 *The phase image for the period P=120s*

4. CONCLUDING REMARKS

Carbon reinforced composite materials, used herein, are composites of particular interest for the vehicles and aerospace industry [11, 13, 16, 17]. Due to the high heat conductivity of carbon, thermography is limited as an NDT tool, while for here described approach the thermograpy is showing high capabilities.

For the case of less conductive reinforcements, such as glass fibres are, thermography as an NDT tool is providing even better results [8]. The presented approach is based on the lock-in method where the heating period modulation is chosen depending on the thermal properties, thickness and expected depth of examined material. In order to detect damages at different depths, it is necessary conducting several tests with different excitation periods. When higher frequencies are used, only shallow damages are revealed. Moving towards lower frequencies, deeper damages are revealed. The presented approach is eliminating influence of the uneven heating, environment reflections and surface coating. Lock-in method allows fast inspection of a large surface area, making it simple and applicable for industrial applications. Further research will be concentrated on the quantity analysis of damages, such as revealing area and depth of damage.

5. REFERENCES

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