The Application of IR Thermography to the NDT and Thermal Stress Analysis

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ABSTRACT *- Advantages of using Infrared Thermography as a Non Destructive Testing method is resulting in the growing interest for method in the field of composite structures. The presented research is focused on Glass Reinforced Polymer structures. Methods, such as Pulse Thermography, Pulsed Phase Thermography and Lock-in Thermography are referred. The Pulse Thermography together with the gradient based approach is addressed for the case of wind turbine blades. The gradient based image processing approach enables filtering out anomalies with the goal to make clearer distinction and evaluation. The Thermoelastic Stress Analysis, as a method similar to the Lock-In Thermography, is presented as an NDT approach for evaluating stress distribution of cyclic loaded structures.*

1. INTRODUCTION

The infrared (IR) themrography is becoming more and more popular method in Non Destructive Testing (NDT) of polymer materials. It is already a recognized method when evaluating passenger planes. When writing this article the first Boeing 787 Dreamliner has started commercial flights. The 787 is a composite airplane made mostly from carbon reinforced fiber composites, what is enabling savings in fuel up to 20% and more robust aircraft structure. There are numerous examples of using the IR thermography in detection of anomalies. In this article a short overview of methods is presented together with some recent developments performed by the team of authors.

IR thermography can be divided in two groups, active and passive thermography. When observing polymer composite material with stationary temperature, nothing except the different surface emissivity can be observed on the thermogram. Thus, an excitation is needed. The excitation can be heat pulse (PT – Pulse Thermography) or group of pulses in sinusoidal form (LT – Lock-in Thermography), or their combination (PPT Pulsed Phase Thermography). The excitation can be ultrasound (rarely used) or sinusoidal structure loading (TSA - Thermoelastic Stress Analysis). In LT and TSA sinusoid heating or loading is resulting in structural heat response that will be sinusoidal as well, but with a shift in phase and amplitude, what is the base of LT and TSA approaches. Electromagnetic loading can also be used for generating excitation, what is not so common approach. Recently, when evaluating the aircraft structures heat blankets (a heater in form of soft silicone cover) are used to generate the heat flow. A good overview of methods can be found in [1].

Passive thermography is also used as a NDT method for cases where thermal gradient generated after landing is used, what is making the approach in fact an active one. The typical example is the Boeing procedure of detecting the humidity infiltration *zones by performing the thermal acquisition of a plane within the first hour after landing. If humidity penetrates the polymer structure it will turn to ice and significant temperature difference will be generated in affected zones, e.g. humidity penetration in composite flaps, what is a common problem.*

Although the presented research is performed with a cooled middle wave (MW) IR camera, our goal is to present and develop NDT methods applicable to common long wave (LW) cameras and acquisitions of real structures out of controlled laboratory conditions. A short overview of NDT thermographic methods is given and a NDT procedure applicable to common LW IR equipment is presented.

2. REQUIRED EQUIPEMENT

To perform IR acquisition generally two types of IR cameras are used. MW cooled cameras are mostly based on photonic detectors, while LW non cooled cameras are mostly based on bolometric detectors. Although non cooled MW do have a cooler element (e.g. Peltier cooler) or electronic stabilization (e,g. P version of FLIR cameras), the role of cooler is to keep constant working temperature, not to significantly cool down the Focal Point Array detector (FPA). Photonic FPA detector enables high frame rates (more than 400 Hz). This is not the case with bolometric detectors where changes in electric resistance enable lower frame rates (around 20 Hz). If fast occurrences have to be captured, cooled LW camera working on cryogenic temperatures around -200°C is required. Thermal sensitivity of cooled MW cameras is mostly around 0.02°C, while sensitivity of LW cameras is mostly from 0.1 to 0.08°C (latest releases can reach 0.05°C). While estimating the thermal sensitivity it is important to find out what was the temperature when sensitivity was measured as higher temperatures are resulting in better sensitivity! IR cameras are based on one lens enabling one field of view (FOV), i.e. the lens angle. Standard lenses (FOV around 25°) are not suitable for acquisition of distant objects. As a camera for each lens must be calibrated, mostly it is more convenient to buy a higher resolution camera than the one with lower resolution and pair of lenses with standard and narrow FOV. Although appropriate in thermal surveys of buildings, when used for NDT wide angle FOV lenses are problematic due to the significant image distortions. When comparing cameras it is important to compare the actual spot size ratio (SSR) as well.

To create the heat wave required for PT, PPT or LT, Xenon flash lamps and Halogen lamps are used.

In case of acquisitions performed on fast cooling materials such as metals (high heat conductivity) the heat pulse has to be applied in a relatively short time [2, 3, 4]. The cooling effect is short and counted in milliseconds. Fast cooling materials require cooled MW high frame rate cameras. The heat source is a Xenon flash lamp capable of producing at least 6 kJ of energy in less than 20 ms, which implies special requests on needed equipment (the price of flash lamp and flash generator around 6000 EUR). Flash based method is applicable for slow cooling materials such as composites, e.g. references [1, 5, 6, 7, 8]. They can be evaluated with significantly cheaper equipment, i.e. bolometric LW cameras and Halogen lamps. Although it seems logical to use IR lamp as a heat source, the post heating response depends upon the heat source frequency, thus the IR lamps are not suitable. Therefore, in case of slow cooling materials [7, 8, 9] such as GRP (low heat conductivity) a heat source based on a Halogen lamp enables visualization of material anomalies such as fractures, delaminations and air pockets, as well as it enables locating hidden structural members and reinforcements. The method is applicable to the carbon reinforced composites as shown in references [1, 5, 6, 10].

The presented research is conducted with a 1 kW Halogen lamp and a cooled MW InSb 320×256 pixels IR camera. In the master thesis research [10] the optimal position of the camera and the lamp is evaluated.

According to [10] the lamp is positioned normal to the surface within the distance of 1 to 2 m. These conclusions are valid for observed GRP structures and 1 kW Halogen lamp. In here presented examples the camera was positioned 1 m from the surface (the distance depends upon the specimen size and the angle of camera lens) and with a 15° offset from the normal direction. This camera offset is particularly important when using cooled MW camera where FPA reflection cooled down to -200°C will influence the image. For LW bolometric cameras the 15° is a strong recommendation.

3. PULSE HEATING THERMOGRAPHY

*Pulse Heating Thermography or simply Pulse Thermography (PT) is based on a heat pulse generated by flash or halogen lamp and followed by the thermal acquisition. Here the discussion is limited to the halogen lamp applied on a GRP material. The pre-damaged specimen of four layered rowing GRP is heated and cooling process is recorded (**Figure 1**).*

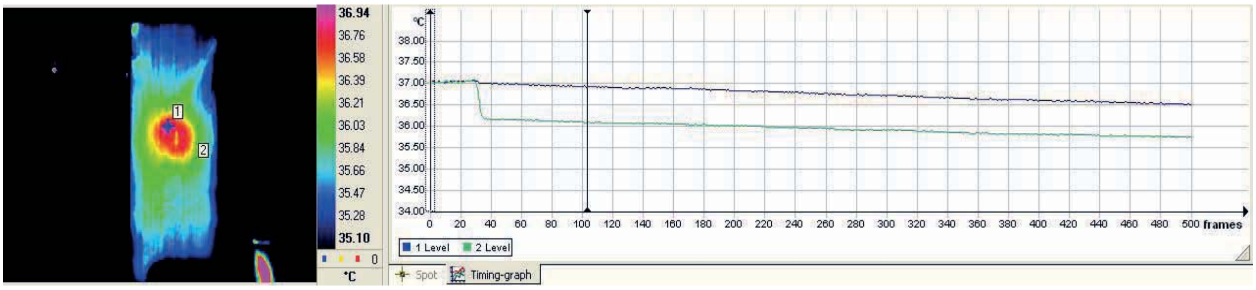


Figure 1 *Different cooling path for damaged and undamaged regions at 50Hz frame rate*

*The blue (upper) line represents the temperature of damaged zone while green (lower) line is the temperature of undamaged zone. First 30 frames of the diagram are last moments of heating, where temperature is strongly influenced by the halogen lamp reflections. After removing the heat source, cooling starts. Observed points on the diagram in (**Figure 1**) have different temperature and cooling gradient. After some time the equilibrium will be reached at the room temperature (not displayed on the diagram). Approximately 10 minutes are required for structure to cool down at the stage where are no detectible differences.*

*The displayed diagram of 500 frames at 50 Hz corresponds to 10 seconds of recording. The cooling dynamics and thermal contrast ΔT (i.e. the difference between two curves) depends upon the damage depth. The thermal contrast ΔT between two observed points is diminishing during the time, as depicted in **Figure 1**. The thermal contrast between damaged and undamaged regions can be observed during the heating, but the reflections of heating lamp are strongly influencing the image.*

*There are applications, e.g. references [1, 5, 6], where complete cooling process is evaluated and whole sequence of frames is processed. Here we are limiting analysis to the first frames (e.g. frame 40) where there is enough thermal contrast between damaged and undamaged regions. Such an approach is appropriate for thinner structures and instant on-the-field NDT. The approach is applicable to the LW camera, e.g. **Figure 2** where acquisition on the same specimen from Figure 1 is performed by a 120x160 pixels LW camera with sensitivity of 0.12°C.*

In case when thicker GRP structures are evaluated, a deeper analysis of the whole cooling interval has to be performed. Mostly approaches are based on processing the thermal contrast between intact and damaged part, what improves evaluating the depth and size of damage [1].

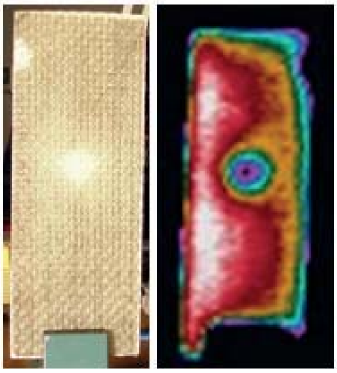
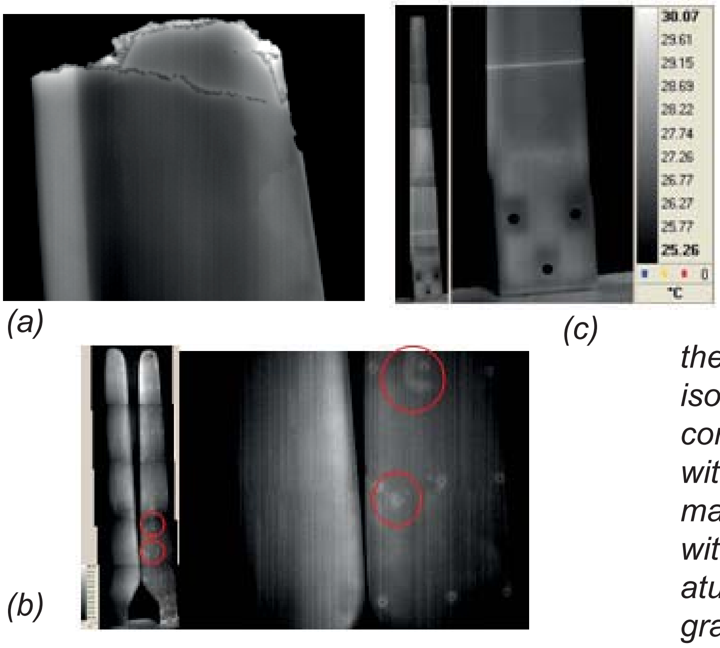


Figure 2 *NDT performed by LW camera*

Some examples of NDT detections are depicted in Figure 3. Cases include detection of fractures, air inclusions, structural elements and delamination.



(a)

(c)

(b)

Figure 3 *Detection of fracture (a), air inclusions in the gelcoat (b) and reinforcements of a wind turbine blade (c)*

4. LOCK-IN THERMOGRAPHY

The Lock-in Thermography is a powerful method based on the fact that sinusoidal heat pulse will cause a sinusoidal response, but with a shift in phase, frequency and amplitude. Tests at several frequencies have to be applied in order to capture shallow (high frequencies) to deep (low frequencies) defects. Although such NDT process requires complex data processing, the method is capable of giving precise data of damage depth. Method's main advantage is less sensitivity to variations in surface emissivity, geometry differences and uneven heating. The LT requires cooled MW cameras, Xenon flash lamps and a flash generator capable of generating sinusoidal heat waves with modulated frequencies and amplitudes.

5. PULSED PHASE THERMOGRAPY

The Puled phase thermography is a combination of PT and LT. The approach is based on a fact that every PT pulse can be represented through the sum sinusoids with variable amplitudes and frequencies, and vice versa, from a pulse set of sinusoidal waves can be extracted using Fourier Transformation. The obtained phase delay is used to evaluate the thermal contrast resulting in thermal images free from influences such as uneven heating [1].

6. GRADIENT BASED APPROACH

Gradient based approach to PT is an image processing method proposed in [15, 16]. The idea came from standard thermographer's procedure when analyzing thermograms, i.e. sliding the isotherm. An isotherm in the IR image processing is a line connecting field of apparent temperatures within a thermal range of interest. The normal to the front line of isotherm coincides with the temperature gradient. The temperature gradient function is

$$\mathrm{grad}\, T = (\partial T/\partial x, \partial T/\partial y), \qquad (1)$$

where T(x,y,t) is a temperature of each pixel forming the thermal image at observed (constant) time t, i.e. coordinates x, y are horizontal and vertical directions of a pixel position in the pixel map. Such an image processing enables flattening the differences in thermal signal with lower gradient, while keeping visible zones with higher thermal gradient, i.e. it enables visualizing the transition zones between anomalies and intact object. The method filters out parasitic influences caused by uneven heating.

In ***Figure 4*** *the gradient function is performed on the PT image of ruptured blade. The delamination near the trailing edge is more pronounced and damaged zone is clearer.*

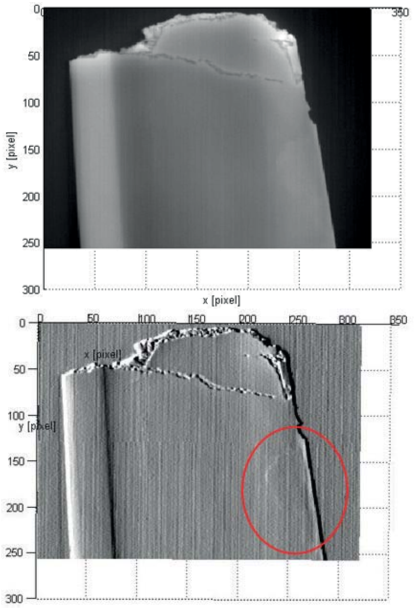


Figure 4 *PT thermogram of the ruptured blade and the corresponding thermal gradient image*

Additional improvements in thermal image clarity can be reached if low pass filtering is performed prior to gradient function. The low pass filter is a common tool included in thermal imaging software. Therefore, the method is simple as common PT, reduces problems with unequal heating and similar to LT. There are examples in literature where gradient based image processing has been used as an image analysis tool in Caustics [17, 18]. Caustic is a NDT method used for crack propagation evaluation of composites.

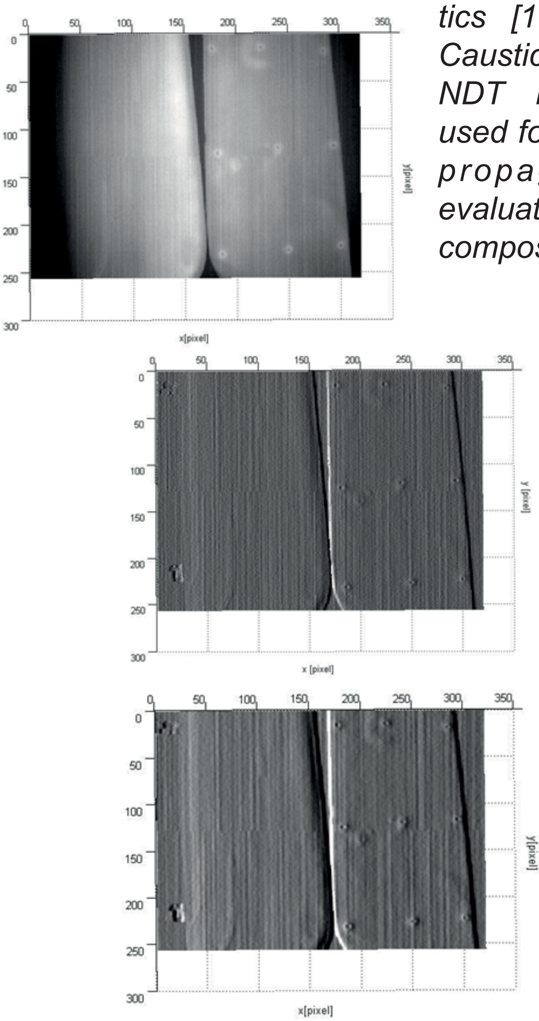


Figure 5 PT thermogram, gradient image and low pass filtered gradient image

7. THERMOELASTIC STRESS ANALYSIS

The Thermoelastic Stress Analysis (TSA) is a method similar to LT, but instead of sinusoidal heating, sinusoidal loading is applied. Thus structure has to be loaded, what is the main drawback of the method. Another request is that quasi-adiabatic thermal condition is needed. This condition is fulfilled at the frequencies of approximately 10 Hz for the case of metals, and lover frequencies for GRPs case (down to 3 Hz). In TSA a cooled MW camera is required and lock-in (additional hardware component) is picking up the sinusoidal signal. The load, displacement, or acceleration can be used as the sinusoidal source signal required for the input to the lock-in component. It is possible to visualize stress distribution even without the lock-in component [19], but readings of stress are inaccurate.

The method of TSA is based on the fact that each material heats when compressed, and cools when starched within elastic limits [20]. The plasticity or rupture is causing very strong heat effect easily detectible by a LW camera. When evaluating plasticity LW cameras have to be used with caution due to the fact that it is not possible to clearly locate affected zones. The governing relation is the thermoelastic equation relating the first invariant of principal stress tensors with temperature differences ΔT, i.e.

$$\Delta T = \frac{-\alpha T}{\rho C_p}(\sigma_1 + \sigma_2), \qquad (2)$$

where α is the coefficient of thermal expansion, T is the room temperature, ρ is the density and Cp is the heat capacity at constant pressure. All these parameters, except the first stress invariant, are constant for observed object. It is important to mention that crucial in obtaining correct stress readings is the evaluation of the emissivity parameter. The method is similar to Strain Gauge (SG) method with difference that result of SG method is giving reading of a single strain gauge, while LT gives reading of whole visible surface making the TSA a full field method. The output of the TSA is the first invariant of principle stresses $I1=\sigma1+\sigma2$, making the method similar to Photoelasticity where $\sigma1-\sigma2$ is the output of analysis.

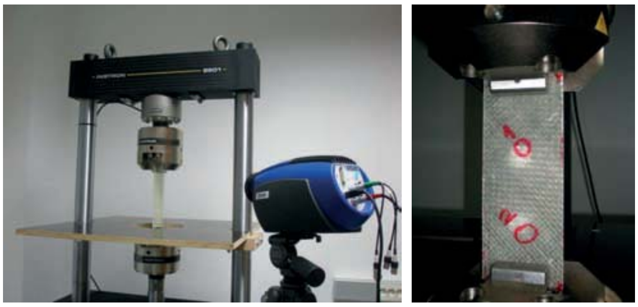
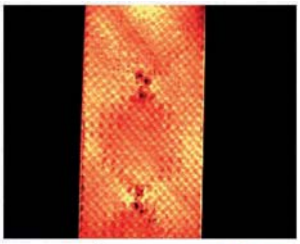


Figure 6 Dynamical loading machine and damaged GRP specimen [9]

In Figure 6 and Figure 7 the damaged specimen with controlled impact load is evaluated with means TSA and PT method. Details as material, impactor and experimental setup are presented in [9]. Figure 7 depicts the first invariant stress distribution of cyclically loaded damaged specimen and intact specimen. Left thermogram in Figure 1 is the specimen depicted in Figure 6 with two damaged zones. For this specimen, the 0 MPa stress at the points of impact is caused by the fact that fractured glass fibers cannot carry load, i.e. they are unloaded locally. The area surrounding damage shows no influence on the stress re-distribution pattern. The pattern is caused by the fibers woving direction and setup of fibers carrying the load. From the presented analysis of damaged composite material the influence of damage on the structure integrity can be evaluated. With such an approach based on the TSA damage itself can be located by finding unloaded fibers. By using the TSA delamination damage was not clearly visible. Thus, the method is a reliable only for detecting the damaged fibers, while delamination detection requires different techniques such as PT, PPT or LT.



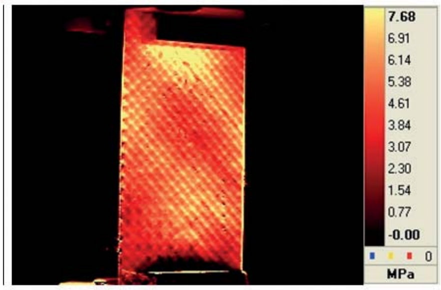


Figure 7 *The stress distribution of damaged and undamaged GRP specimen*

8. CONCLUSIONS

Within this paper an overview of relevant IR methods for NDT of GRPs and other composite material is presented. Although researches are performed with cooled MW camera, it is shown that PT is applicable to the uncooled LW cameras as well. The Gradient based approach is a simple image processing method applicable to every thermogram if it can be extracted in matrix form. To process such an image the standard grad function in MatLab can be used. When evaluating methods it is important to distinguish what method are applicable in real life on the field conditions when NDT is carried out.

9. REFERENCES

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