ADVANCES IN AUTOMATIC CHARACTERIZATION OF DEFECTS IN CFRP BY INFRARED THERMOGRAPHY

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Abstract. Infrared Thermography applied as NDT is reaching nowadays a high level of development. The validity of this technology to detect multiple types of defects in metallic materials as well as in composites has been demonstrated; and together with its characteristics of quick inspection, health safety and feasibility of remote and contactless inspections make Infrared Thermography one of the most promising recently developed NDT technologies.

Infrared thermography applied as NDT has been under development for several years. However, one of the main disadvantages that currently affect this application is the lack of a common agreement on the approach to be followed to correctly identify the nature of defects. Therefore, sometimes indications are interpreted as defects when they do not correspond to damaged areas, or even indications are interpreted as other different types of defects that have similar behavior.

The objective of this study is to develop a process of characterizing defects present in composite materials with infrared thermography by analyzing the thermal response to different stimuli and different signal processing techniques. The defined procedure is finally automated to characterize defects effectively.

To achieve this objective three common defects occurring in composite materials have been selected. These defects have been inspected using the same IRT technique and subjected to data processing methodologies for improving the detection level and to proceed to the characterization. The characterization of each defect was performed by analyzing the results obtained in the processed data, identifying the characteristic points and tendencies of the responses of each type of defect. As a result of this analysis, an effective methodology for the characterization of defects has been defined, which allows to be implemented into a neural network system for automating characterizations of defects in NDT inspections with IRT.

1. Motivation

In determining the useful life of aircraft components and prevent potential failures, manufacturers must verify the integrity status of materials throughout the entire product life cycle, from design to production and also in service. The costs and time saving by using nondestructive inspection techniques to detect surface and internal defects in composite and metallic materials is essential for aeronautical industry to achieve a high level of competition.

However, the aviation sector is in constant evolution and requirements are becoming increasingly demanding. Moreover aeronautical sector is tending towards a collaborative engineering so it also requires a change in design engineering and manufacturing, which must take into account the methods of inspection from the earliest stages of design of the aircraft. Another key point is to integrate technologies and inspection processes to the global aircraft manufacturing process and not individually.

The aviation industry is an industry that continues to progress steadily and where new technologies and materials appear. One of the main objectives is currently focused on increasing productivity. Often technological developments are very advanced but are too complex to complicate the start of production. This is translated to a real necessity of more simple and productive NDT techniques to adapt to the demanding levels of production and service in an industry that increasingly demands more aircraft and whose expected growth rate is so significant.

Among the new NDT techniques that can provide solutions to these requirements of the aeronautical industry for the NDT techniques highlights IT. As NDT technique, the IRT compared to conventional techniques used currently has the following advantages:

- Contactless inspection capability.
- Quick inspection.
- Simple and manageable equipment.
- No risk of dangerous radiation.
- Ability of inspection large areas and small zones of detail.
- Results provided as images in digital format.

2. Active Infrared Thermography as NDT Application

Infrared thermography is a technology that allows visualizing the temperature of a surface accurately and without contact. Considering Mathematical theorems and physical principles we can translate measurements of the infrared radiation of a body into temperature measurements.

However, the field of application of this technology goes further beyond the simple temperature measurements, covering both industrial applications and research and development. In the case of application as a tool for NDT, there are two different approaches in implementing TIR: active and passive application.

Passive IRT applications refer to those cases in which no stimulation of external heating or cooling to cause a flow of heat inside the body inspected is used. The object under study produces a known pattern of temperatures because of it is involved in a process which produces heat itself.

In active thermography external stimulation is used to induce a flow of internal heat in the studied object. An internal defect affects the established heat flow producing a thermal contrast on the surface which is detected by a IR sensor.

2.1 Stimulation Techniques

Depending on the technique or heating mode that is used in active IRT we can find the following variants.

- The pulsed IRT involves the application of a short pulse of heat on the object and record the cooling evolution of the temperature in the surface of the specimen.
- The Step Heating or long pulse IRT, the object is continuously heated in low temperature level.

- The lock-in IRT is based on the generation of heat waves within the inspected specimen and synchronously monitoring the oscillating temperature fields.

The most common excitation technologies applied in active IRT for nondestructive inspections are:

- Optical excitation. The heating is produced by means of lighting devices such as high energy flash lamps, halogen lamps, infrared lamps, and so on.
- Mechanical excitation. Mechanical waves are introduced in the material by means of a piezoelectric. These injected ultrasonic waves propagate inside the material, cause particles of the material to vibrate and thus produce heating by hysteresis or friction in those zones with presence of defects.
- Inductive excitation. This technology uses magnetic fields as excitation source. Electric currents (Eddy-current type) are induced in the material to inspect by exposing to these fields. Finally, zones with presence of defects will produce heat by Joule effect thus being detected by IR sensor.

Each type of defect in a specific material provides a different response to each IRT excitation technique. It is essential to find the most suitable inspection strategy (deposited energy, distance between heat source and object studied, heating duration, ...) for detecting each type of defect, and also the parameters that characterize each one (time of occurrence, maximum contrasts, ...).

2.2 Data Processing Algorithms

In addition to the results of the IRT inspections presented in images, numerical data of temperature field are also obtained, and all in digital format, which can be conveniently stored and reviewed or even further processed.

Nowadays not only the direct measurement of temperatures are used in IRT inspections to evaluate the state of a material, but also the collected data is processed to improve the detection of contrasts that can identify the presence of an anomaly. The post-processing techniques include the application of various types of mathematical algorithms to data acquired in the inspections. With its application improved detection levels are achieved, making possible the location of defects which might not be detected in the initial results (raw).

2.2.1. Fourier Transform

The Fourier transform applied to a temporal sequence of thermal registers is a breakthrough in the treatment of thermal signal. Fourier Transform allows passing the time domain to the frequency spectrum by the following relationship:

$$F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) e^{-j2\pi nk/N} = Re_n + iIm_n \qquad (1)$$

where n is the frequency increase (n = 0, 1, ..., N); .Δt is the time interval between consecutive acquisitions and Re_n and Im_n are the real and imaginary parts of the transform, which can be combined to extract the amplitude A_n and phase φ_n values:

$$A_n = \sqrt{Re_n^2 + Im_n^2} \quad , \ \varphi_n = tan^{-1}\left(\frac{Im_n}{Re_n}\right) \qquad (2)$$

2.2.2. Thermal Signal Reconstruction (TSR)

The TSR algorithm is based on the ASTM E 2582-07 standard, and is registered under US Patent 6,751,342 B2 June 2004 (Esteven M. Shepard). This method adjusts the temporal evolution of the temperature of each pixel to a polynomial of n degree, of the type shown in the following equation:

$$T(t) = a_n t^n + a_{n-1} t^{n-1} + \cdots + a_1 t + a_0 \tag{3}$$

Once the polynomial is built it is possible to apply other operations to it, such as successive derivation, which will provide different improved results.

3. Strategy followed

The methodology defined to achieve the objective of characterizing the defects detected by active IRT is based on 3 key parameters: the type of defect under study, the equipment and application procedure employed in the inspection, and the measurement criteria, or metric, used to evaluate the results.

3.1 Specimens inspected and defects

For this study 3 common defects encountered in aeronautical CFRP components have been selected and analyzed: delamination, porosity and disbond.

3.1.1 Delamination in CFRP Solid Laminate

Delamination is probably the most common defect in composite material produced by the separation of different layers that form the laminate.

One cause of the occurrence of this type of defect is a direct impact on the surface. In this study impacts of different energies carried out on tubular pieces of square section made of CFRP have been analysed. The impact energy applied was 5, 10 and 15 Joules applied with a homologated impactor system.

Fig. 1. Images of a CFRP specimen for the study of delamination produced by impact.

3.1.2 Porosity in CFRP Solid Laminate

Porosity is an inherent characteristic of composite materials. They all have certain level of porosity depending on the manufacturing process employed. However, these levels of porosity must be maintained under certain limit to preserve the mechanical properties of materials.

Specimens used to characterize the porosity defect were the same specimens that were used for the characterization of defects of delamination. These pieces were made by RTM manufacturing process during which some kind of loss of conditions took place that caused excessive levels of porosity in some parts.

3.1.3 Debonding between CFRP and Ti in Solid Laminate

Debonding is a common failure of structures composed of various materials. Problems arise when joining different materials together. The most common option to typically face this problem is by using adhesive glue. However, this process is complex leading sometimes to areas where this union could not be performed properly, resulting in debonding defects.

The specimen used to characterize the behavior of debonding defect is a real aircraft component; specifically it is a leading edge of CFRP with its front zone reinforced by a titanium plate. Both parts are manufactured separately and finally joined by a gluing process.

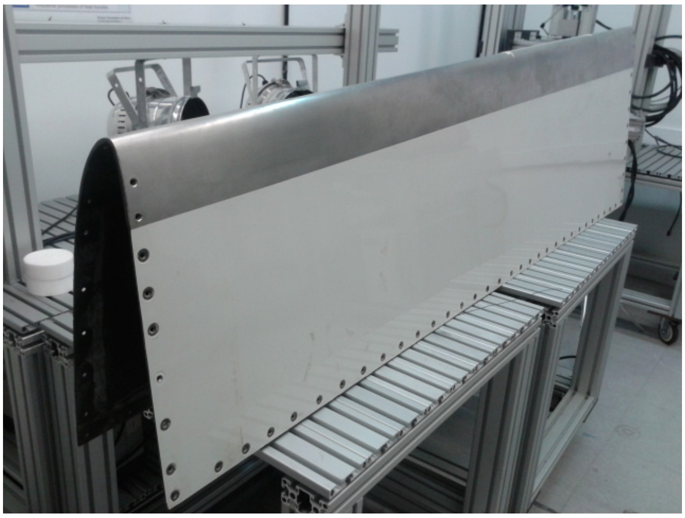


Fig. 2. Image of the component containing defects of debonding between CFRP and Ti plate.

3.2 Inspection Procedure

In this study all the specimens were thermally excited using an optical method. Specifically, optical step heating thermography was the one selected among the different options. It was selected due to the possibility to control the injection of energy into the material during the entire inspection, which allows a precise control of the highest temperature level, preserving at the same time the capacity of non-contact inspection of the IRT technology.

Optical stimulation was applied using two halogen lamps of 1000W at 60% capacity. The lamps were turned on for 10 s to heat the specimen. After the lamps were turned off, the temperature decay is also recorded for 10 s more, making a total of 20 s for the whole inspection process.

Infrared images are acquired using a FLIR SC5500 camera. This camera is equipped with a cooled Indium antimonide detector that operates in the 2.5–5.1 µm waveband. The FLIR SC5500 produces thermal images of 320x256 pixels with 12 bits per pixel and a thermal sensitivity of 20 mK. Although the camera has a maximum frame rate of 383 Hz, the experiments were recorded at 50 Hz to reduce the number of acquired images.

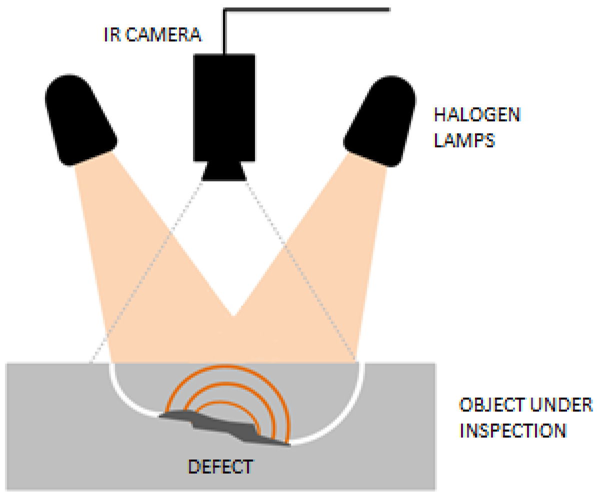


Fig. 3. Illustrative scheme of the lay out of the active IRT inspection conducted in the study.

3.3. Defect Measurement Criteria

The SNR metric is used in this study to objectively assess the level of the signal-to-noise ratio of the indication detected in the inspections. The quantification of a defect is based on the definition of two areas:

- Defective area, which encloses points from the IR image inside a detected indication.
- Reference area, which encloses points outside the detected indication thus considered sound area.

The reference area is a defect-free area used to calculate the thermal contrast and is selected close to the indication so it is considered to have received the same excitation energy under the same conditions as the defect. This also minimizes errors in SNR calculations due to non-uniform heating.

The SNR metric for a defect is calculated as shown in Eq. (4), where Def_μ is the arithmetic mean of all the pixels inside the defective area, Ref_μ is the arithmetic mean of all the pixels inside the reference area, and Ref_σ is the standard deviation of the pixels inside the reference area.

$$SNR = 20log_{10}\left(\frac{|Def_\mu - Ref_\mu|}{Ref_\sigma}\right) \quad (4)$$

Another important parameter of an image to be considered when detecting defects is the sharpness. This quality factor has been traditionally neglected in most studies. The main reasons are that sharpness is difficult to quantify and there is no clear procedures defined in active infrared inspection. In this work, we propose the magnitude of the gradient as a metric to measure the sharpness of the image. It can be used to describe the sharpness of the edge in the image.

The gradient must be calculated using an approximation of the derivative along a direction as show in Equations (5).

$$\frac{\partial f}{\partial x} = \lim_{\varepsilon \to 0} \frac{f(x+\varepsilon)-f(x)}{\varepsilon} \qquad\qquad G = \sqrt{\left(\frac{\partial I}{\partial x}\right)^2 + \left(\frac{\partial I}{\partial y}\right)^2} \qquad (5)$$

4. Results obtained

4.1 Detection and Characterization of Defects

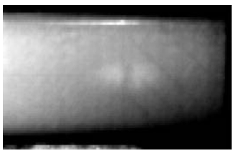
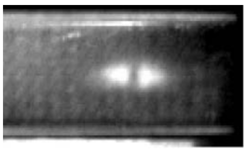
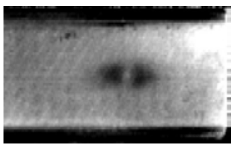
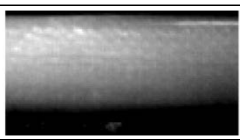
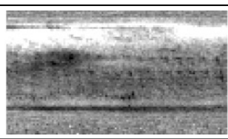
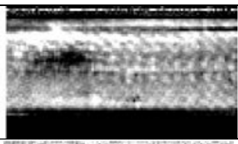
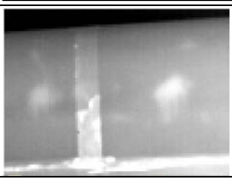
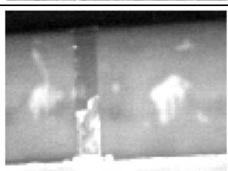
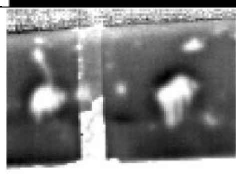
A total of 42 specimens containing delamination defects produced by impact were inspected by active IRT technique, being able to detect all the points of impact as well as the damaged area, which was subsequently validated by ultrasound A-scan inspection. Impact points were detected efficiently in all cases without the need for processing due to the trace of the impactor head left on the surface. However, the areas affected by delamination required additional processing of the initial data for being completely detected.

Together with the impacts these specimens also presented zones of excessive levels of porosity. The detection of this type of defect was not as straightforward as in the case of delaminations and it was necessary to apply processing algorithms to obtain indications in all cases. After the application of algorithms the detection was possible and the analysis feasible.

Debonding defects were especially easy to be detected owing to the difference of thermal diffusivity of the materials that constitute this component. 20 different zones of debonding were inspected by active IRT. The raw results showed clear detection of debonding and the processed data were used to determine the level of severity afterwards.

Active IRT inspections were conducted to all the specimens, the acquired thermal signals were processed both to improve the level of detection and analyze the behavior, and finally the results were contrasted by checking with certified UT NDT technique. Some of the resulting images from the experiments can be seen in Table 1.

Table 1. Examples of the raw and processed results obtained in the inspections with IRT.

	Raw	2^{nd} derivative	Fft phase
Delamination			
Porosity			
Debonding			

The characterization of each defect was performed by analyzing the results of the inspections with IRT as well as the processed data, identifying the characteristic points of the responses of each defect. They have been identified the relative maximum and minimum points, and the instants or frequencies at which they occur during the evolution of the inspection process, making it possible to established the range of values that each defect takes in every case.

Delamination defects presented an early minimum value in the first derivative of the tsr processing and another relative minimum after the absolute maximum. This defect also presented a second relative maximum at the end of the sequence. Porosity defect also presented an early minimum but the instant of appearance was later than the case of delaminations. Porosity only presents one maximum at the end of the sequence, while the debonding defect presented only one maximum as well but at early stages of the sequence of data.

Comparing the second derivative of the tsr processing we can distinguish the behavior of the three defects. Thus delamination shows a clear double maximum in the middle of the sequence while the porosity only presented one. Debonding was clearly identified in this case since it shows an absolute minimum in later stage of the data, situation never found in the other defects. Final, analyzing the phase of the FFT analysis we are also capable of characterizing these three defects. The frequency at which the minimum SNR occurs is higher for the debonding while the stationary value of the SNR is negative for delaminations and positive for porosity defects.

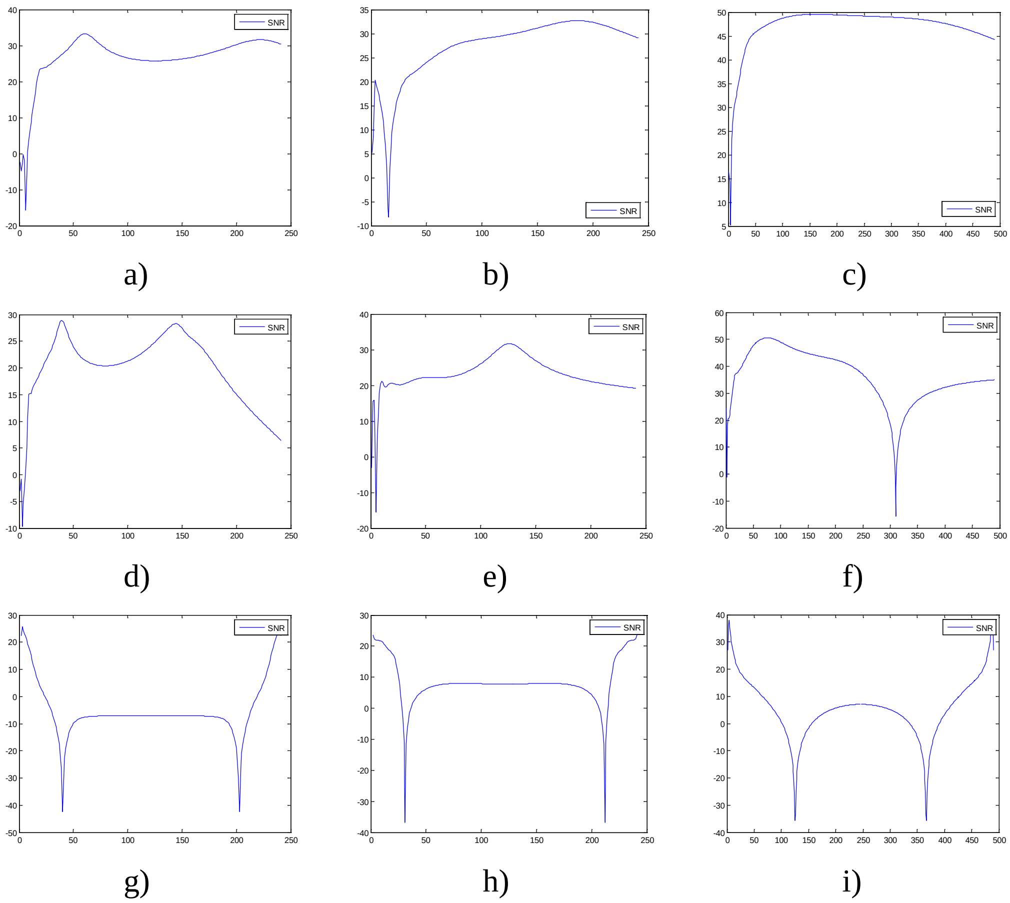


Fig. 4. Examples of graphical representation of the behaviour showed by defects under different processing algorithms. First derivative of tsr: a) delamination, b) porosity and c) debonding. Second derivative of tsr: d) delamination, e) porosity and f) debonding. Phase of FFT: g) delamination, h) porosity and i) debonding

To check the validity of the results and conclusions obtained a final validation study was carried out with the blind inspections, including false indications produced by surface contaminations, being able to effectively differing among the defects with a correct characterization.

5. Conclusions

In this study the automatic classification of defects detected by active IRT techniques is proposed. To achieve this goal three typical defects occurring in composite materials have been analyzed: surface delamination by impact, high concentrated porosity and debonding between CFRP and Ti. These defects have been inspected using the same active thermographic inspection technique. In this case necessary stimulation to reveal defects is generated by halogen lamps in step heating conditions. Not all the inspected defects were effectively detected in the initial inspection with raw results. Delaminations produced by 5J energies and moderate levels of porosity were only detected after the application of processing algorithms.

The algorithms for processing the raw data provided a substantial improvement of the level of detection and also, and probably more important, provided thermal behaviors of the defect under different perspective. Therefore in the process of characterizing the defects they have been considered the both the initial results and also the processed ones. However, not only numerical information resulted helpful in the task of characterizing a defect. It has been observed that each of the three faults occurs with a distinct shape. Delaminations by impact exhibit a butterfly shape with a healthy central zone of elastic deformation, porosities appear as irregular accumulations and debonding show circular shapes with clear contours of transition.

After analyzing the results obtained by the application of the processing algorithms, characteristic points for the different behaviors related to each algorithm have been identified. Among them relative maximum and minimum, together with the instants and frequencies of occurring, were identified thus establishing the possible range of values for each defect in each analysis situation. A final validation task was carried out with positive results.

The characterization analysis carried out in this study provides an extensive knowledge of the behavior of several of the most common defects in composite materials. These results represent an advance in the development of a simple, quick and flexible NDT inspection technology towards the industrial application of the active IRT. The next step in this process could be the automation of the characterization process by implementing the information gathered in the programming of a neural network. This way being capable of detecting and determining the presence of defects and define the area affected by them, and in more advanced stages, even determine the volume of adhesive missing, the energy of the impact that caused the delamination or the precise concentration of porosity.

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