Research on the effect of test parameters on signal contrast and accuracy of determining the size of a defect

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Abstract. Currently, is used several non-destructive testing methods for detecting defects in the composite materials. The most potential is methods non-contact scanning for a large surface area with relative insensitivity to environmental disturbances. In this regard, are developed methods for defect detection in composites, all of which have own peculiarity. A fundamental difference concerns the overall length of time is required for non-destructive testing and analysis of thermographic data from the infrared camera, first of all, for large-scale structure. This research has been conducted a quantitative way of analyzing data to optimizing the testing parameters in terms of testing time and signal-to-noise ratio. In particular, were carried a few tests out on stringers of carbon fiber reinforced panels. These tests included lock-in thermography technique with simulated defects, which has been used for finding parameters to correct detect dimensions of defects.

1. Introduction
The concept to increase the proportion of composite materials for constructions and components is a normal practice in a lot of areas modern production, aviation, aerospace and shipbuilding industry. But in spite of the high strength characteristics, the presence of the defect on the surface of composite material may be collapse changed robustness of the structure, so timely non-destructive testing is important on assessing residual strength for a structural component or construction. This’s demonstrated in the literature [1].

Currently, is used several non-destructive testing methods for detecting defects in the composite materials: ultrasound [2–4], sherography [5], x-ray [6], electrical potential technique [7], thermography [7–12] and also their combination if it is necessary for detection different kinds of defects quantify. Methods of active thermography are of particular interest, cause method’s a really quick and easy for inspection of large-sized constructions. This has an impact on the reduction in the time, alleviation of the financial burden of maintenance and repair organizations aviation technics. Also, possibly the automatization of procedure for inspection and analyze data.

The best time setting for testing/analyze data relationship offered in thermography is techniques as Lock-in (LT), Pulsed (PT) and Stepped (ST/SH). These methods belong to active thermography, it’s mean to using a heat source for periodically exciting the specimen surface of heat waves. The presence of the defect in the composite panel may be detected by monitoring the surface temperature decay of the specimen. The defects appearance is as an area of different temperature to a surrounding sound area and it produces an abnormal behavior of the temperature decay curve [11].

The above-mentioned thermography techniques have been used in number of works for the demonstrating propose of the capacity of thermography to detect defects in carbon fiber reinforced
panels (CFRP) and carbon fiber reinforced panels (GFRP) composite materials. In particular, those techniques have got especially efficient in the evaluation of interlaminar delamination or debond.

For analyzing thermography data and for visualization defects was developed different approaches, such as a modulated heat source. This approach have been used for periodically exciting the sample in a desired range of frequencies and finally, accumulation of data about defects in the sample is described theoretically in the work of Mulaveesala [13], and is demonstrated in the works of Palumbo [14–16], where the analyzed data for lock-in techniques as possible with high-level noise for two parameters: amplitude (A) and phase (φ). Lock-in is effective, exact and to a lesser extent susceptible to external influence than Pulsed and Stepped techniques, but requires more inspection time for sample depending on the size surface and depth material because of a few cycles of testing. However, the results of the lock-in approach have not optimized in terms of the inspection parameters and the signal/noise data relationship offered. In this regard in this work is focused on the phase parameter in the processing thermography data, because of the amplitude parameter is less effective for detection defect area. Conducted several testings on the longitudinal stringers of CFRP in order to consider the impact time to heat up and cool the samples on the contrast signal. In addition, quality analyze data is completed with supporting the semi-automatic algorithms.

2. Theory lock-in thermography

Lock-in thermography is based on the generation heating waves inside to inspection specimen for instance by periodically exciting the specimen surface as shown in Figure 1 [7, 10]. The resulting oscillating temperature field in the stationary regime may be recorded on the distance through its thermal infrared emission by an infrared camera. A thermal wave is reconstructed by measuring temperature evolution over the sample surface: by the algorithm might be obtained information about parameters amplitude (A) and phase (φ) of the thermal wave. Phase data are insignificantly dependent from local optical (surface roughness and etc.) and infrared surface features (as an emission), and the phase signal deeper penetration into the material than of the amplitude signal [7, 10], and this impacts on the analyze results.

![Figure 1. Cycle heating up and cooling time of halogen lamps for Lock-in approach.](image)

The phase parameter has had a close link between depth z and thermal wave:

$$\varphi(z) = \frac{2\pi z}{\lambda} = \frac{z}{\mu}$$  \hspace{1cm} (1)

where λ is the length of thermal wave and μ is length of the thermal diffusion:

$$\mu = \sqrt{\frac{2k}{\omega \rho C_p}} = \sqrt{\frac{2\pi}{\omega}}$$  \hspace{1cm} (2)
where \( k \) is the thermal conductivity, \( W/(m \times K) \); \( \rho \) is the density, \( kg/m^3 \); \( C_p \) is the specific heat at constant pressure, \( J/(kg \times K) \); \( \omega \) is the modulation frequency, \( Hz \); \( \alpha \) is the thermal diffusivity, \( m^2/s \).

Equation (1) might be extended to composite laminates and this displays a limitation the analysis in a near-surface region in high-frequency thermal ways \[11, 17\], while lower modulation frequencies propagate deeper and slowly. A serious weakness method remains that the operator has to change and to perform different parameters for inspection, changing the frequency of thermal excitation for depth evaluation. In Lock-in thermography, a modulated square wave has been shown in Figure 1 with using periodical heating up and cooling the surface specimen by two halogen lamps as a heat source with a power 1.5 kW each. It should be noted that the thermal response of composite material contains data about higher frequencies proportional to the main frequency, as shown in other works \[16, 17\]. And by way of decomposing the thermal response in the time domain as the sum of a singular sinusoidal wave, getting:

\[
T_m(t) = a + bt + \sum_{n=1}^{\infty} \Delta T_n \sin(n\omega t + \varphi_n)
\]

where \( t \) is time, \( s \); \( a \) and \( b \) constants of the model of the material average temperature growth; \( \omega \) is the modulated frequency of the main harmonic, in other words, the first Fourier component, \( Hz \); \( \Delta T_n \) is the amplitude of \( n \) – th Fourier components; \( \varphi_n \) is phase of \( n \) – th Fourier components, \( n = 1,3,4,7 \).

Values of \( n \)th components invent odd numbers, because of the modulated square wave has had heating up and cooling steps, if the experiment has got the three cycles (Figure 1) then the value \( n = 5 \).

3. Proposed method and set-up

In this work has been conducted non-destructive testing on the 6th stringers of CFRP with delamination (Figure 2).

Table 1 is demonstrated stringer in which \( b_1 \) is the dimension of the defect in the front side sample, and \( b_2 \) is the dimension defect of backside sample because of the delamination is cross-cutting nature. The \( D \) and \( L \) are the width and length of the sample. The \( S \) is length connective part in which is the defect.

| Type of stringer | \( b_1, \text{mm} \) | \( b_2, \text{mm} \) | \( S, \text{mm} \) | \( D, \text{mm} \) | \( L, \text{mm} \) |
|------------------|-------------------|-----------------|----------------|----------------|----------------|
| 1D               | 50                | 37              |                |                |                |
| 2D               | 6                 | 11              |                |                |                |
| 3D               | 1                 | 7               |                |                |                |
| 1N               | 27                | 3.1             | 66             | 55             | 290            |
| 2N               | 14                | 24              |                |                |                |
| 3N               | 40                | 39              |                |                |                |

In the NDT standard ISO9712 thermography is considered as a superficial technique, for the composite material, it is more a volumetric technique and it being able to analyze with up to 6–8mm thickness of the structure, i.e. the vast majority of composite components \[12\]. The experimental set up in working order is shown in Figure 2.
Figure 2. Experimental set-up with CFRP stringer

The parameters of non-destructive testing for the detection of delamination in the specimen using Lock-in thermography taking into account different interval of heating up and cooling time in Table 2.

| Modulation Period, s | Frame rate, Hz | Total frames | Number of cycles |
|----------------------|---------------|--------------|------------------|
| 90                   | 2             | 550          | 3                |
| 60                   | 2             | 370          | 3                |
| 40                   | 4             | 500          | 3                |

For analyze the dimension of delamination or rather to obtain estimated defect area (AER) is used the semiautomatic algorithm in MATLAB (Figure 3).
As can be seen, changing parameters non-destructive testing impact on quality results of thermography data. It is necessary to define the optimal balance between the better values estimated defect area and inspection time. Increasing the inspection time depends on the size of the testing area and depth of composite material.

The existence of only the phase signal along the profile doesn’t give in the practical context find out the exact dimension of the estimated delamination area. Available methods are labour-intensive, difficult to achieve and cannot be automaty (Figures 4–6). So, in this work is used a quantitative data analysis. This approach has been widely used for testing time reducing. The theoretical basis of this approach in the work of Palumbo [16] was mentioned. This approach was used in a semi-automatic algorithm in quantitative measured data analysis.

Figure 3. Samples D and N with different parameters of testing.

Figure 4. Phase signal along the profile in samples D and N (sinusoidal wave, modulation period 90s, modulation frequency 0.011 Hz).
The main idea the quantitative data analysis lies in the fact to the values in each pixel which is more than the threshold value is changed in the value 0, and values less are changed in the values 1 this's the delamination area. The threshold value ($Th$) has been defined in the equation (Eq. 4):

$$Th = a[mean(A_d) - mean(A_s)] + mean(A_d)$$

where $A_d$ representing the area with defect, determined by n x n pixels image, centered on the peak value of the signal; $A_s$ is the sound is obtained as previously exposed.

4. Data analysis
The application of the quantitative data analysis approach for lock-in technique allow obtaing binary images (Figures 7–9).

![Figure 5](image1.png)

**Figure 5.** Phase signal along the profile in samples D and N (sinusoidal wave, modulation period 60s, modulation frequency 0.017 Hz).

![Figure 6](image2.png)

**Figure 6.** Phase signal along the profile in samples D and N (sinusoidal wave, modulation period 60s, modulation frequency 0.017 Hz).
Figure 7. Binary images for detection of delamination in samples D and N (sinusoidal wave, modulation period 90s, modulation frequency 0.011 Hz).

Figure 8. Binary images for detection of delamination in samples D and N (sinusoidal wave, modulation period 60s, modulation frequency 0.017 Hz).

Figure 9. Binary images for detection of delamination in samples D and N (sinusoidal wave, modulation period 60s, modulation frequency 0.017 Hz).
5. Conclusion

As was expected, deeper defects appear in correspondence with a higher modulation period (lower excitation frequencies). The main results may be summarized as follow:

- The modulation period of the signal has been given in 60 second and frequency 0.017 Hz is shown even satisfactory results if the estimated defect area is an interval between 33.28 %≤AER%≤59.43 %. And this value AER% is enough to conclude about scrapping status of the component.

- The modulation period of the signal has been given in 40 second and frequency 0.025 Hz can be shown sometimes interest results if the estimated defect area is AER%≤21.77 %. However, the feasibility of this proposal needs to be further explored.

- The modulation period of the signal has been given in 90 second and frequency 0.011 Hz is the best parameters for non-destructive testing, showing enough exact results, but the feasibility using.

- The modulation period of signal has been given in 90 second and frequency 0.011 Hz is the best parameters for non-destructive testing, showing enough exact results, but the usefulness using is achieved for surface of small-scale with the values of estimated defect area in a low interval or multilayer composites with the depth of the defect 6–8 centimetres, since for it necessary a long process of scanning and analyze data.

- In this work lock-in thermography set-up proposed to choose optimal testing times by getting the highest values of signal contrast. A directly dependence of the signal contrast on the time of heating and cooling the surface of the sample has been established, as well as the dependence of the signal contrast on the delamination dimension and depth.

References

[1] Baker AA, Dutton S and Kelly D 2004 Composite materials for aircraft structures (Reston: American Institute of Aeronautics and Astronautics)

[2] Castellano A, Fraddosio A, Marzano S and Daniele Piccioni M 2017 Procedia Engineering 199 1519–1526

[3] Castellano A, Fraddosio A and Piccioni M D 2017 Composites Part B: Engineering 116 122–136

[4] Hosur M V, Murthy C R L, Ramamurthy T S and Shet A 1998 NDT & E International 31 359–374

[5] De Angelis G, Meo M, Almond D P, Pickering S G and Angioni S L 2012 NDT & E International 45 91–96

[6] Nikishkov Y, Airoldi L and Makeev A 2013 Composites Science and Technology 89 89–97

[7] Angelidis N and Irving P E 2007 Composites Science and Technology 67 594–604

[8] Usamentiaga R, Venegas P, Guerediaga J, Vega L and López I 2013 NDT & E International 54 123–132

[9] Yang R and He Y 2016 Infrared Physics & Technology 75 26–50

[10] Badghaish A A and Fleming D C 2008 Journal of Composite Materials 42 1337–1357

[11] Maldague X 2001 Theory and practice of infrared technology for nondestructive testing (New York: Wiley)

[12] Palumbo D, Ancona F and Galiotti U 2015 Meccanica 50 443–459

[13] Mulaveesala R and Tuli S 2006 Appl. Phys. Lett. 89 191913

[14] Palumbo D, De Finis R, Demelio P G and Galiotti U 2016 Composites Part B: Engineering 103 60–7

[15] Palumbo D, De Finis R, Demelio P G and Galiotti U 2017 St Composites Part B: Engineering 117 49–60

[16] Palumbo D, Cavallo P and Galiotti U 2019 NDT & E International 102 254–263

[17] Pitaresi G 2015 ExpMech 55 667–680