

NON-DESTRUCTIVE INSPECTION OF COMPOSITE STRUCTURES USING ACTIVE IR-THERMOGRAPHY METHODS

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În această lucrare este descris modul de detecție a două tipuri de defecți: defecți de tip variație de grosime și defecți interne de tip delaminări, prin metoda de inspecție nedistructivă numită termografie în infraroșu, obiectele inspectate fiind realizate din același material compozit armat cu fibre de carbon(CFRP).

Pentru inspecție s-au utilizat două metode active de termografie în infraroșu, metoda lock in și metoda tranzitorie puls, în vederea determinării parametrilor principali ai celor două metode și a realizării unor comparații între acestea pentru a o alege pe cea mai potrivită.

In this paper are presented procedures aimed to detect two types of flaws: thickness irregularities and internal defects/damages like delaminations, by non-destructive inspection (NDI) method named infrared thermography (IRT), the inspected objects being manufactured from carbon fiber reinforced polymeric laminates (CFRP).

For inspection, two active infrared thermography methods were used, the lock in method and the transient/long pulse method, in order to establish the main parameters of both of them in order to compare which of them is the most appropriate one

Key words: IR thermography, NDI, lock in method, transient method, CFRP.

1. Introduction

In many applications, starting from industrial ones, where quality criteria must be applied to improve the manufacturing process or the in service features, to insulation problems of buildings or cultural heritage items monitoring such as

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pieces of ancient art, there is growing demand for structural integrity, strongly related to the quality of production, health monitoring by NDI and maintenance.

Non-destructive inspection methods must be reliable, efficient, non-expensive, fast and easy to use. Moreover, as materials and processes are constantly changing, inspection techniques should adapt to this evolution, too.

Among various non-destructive inspection techniques (NDI) currently used in industry, infrared thermography (IRT) is a non-contact inspection tool. It is relevant whenever there is a thermal contrast between the inspected object and the surrounding area of interest (surface defects, but also flaws inside the inspected object) [1]. The non-destructive investigation method using infrared thermography is used for inspection of surface and subsurface defects, quality of joints etc. The potential of this method is currently exploited in various industrial or in different other fields.

Based on the correlation between distribution patterns of surface temperatures and thermal properties, a material characterization can be also achieved by the IRT method. Anomalies of heat flow distribution are caused by the presence of a defect or a discontinuity of the analyzed structure. Highlighting these irregularities provides useful information on size, shape and position of discontinuities [2, 3]. In this paper are presented detection techniques targeting two typical defect types that may appear in composite structures: thickness variation (loss of material) and internal defects (delaminations), using non-destructive inspection by active infrared thermography, namely lock in method and transient (long pulse) method.

2. Background of IRT inspections

The principle of infrared thermography (IRT) for non-destructive inspection (NDI) consists in highlighting the relevant differences or gradient disturbances of temperature due to imperfections and deteriorations of the inspected structures. They become visible on the surfaces of these objects.

The domain of infrared thermography is quite recent and covers vast fields of applications. In the industrial context, infrared thermography is used either by the passive approach (by simple observation of the isotherms on the surface of interest) or by the active approach (by stimulating the thermal response of the specimen) [4-6].

Active methods can be either by transmission or by reflection, taking into account the positioning of the heat source and infrared camera with respect to the examined object. The control by reflection technique is the most common and has the advantage to be useful even in the case of one side accessibility of the inspected items. In the present work the main objective is to assess the structural

integrity of CFRP plates with defects by non-destructive inspection methods using active infrared thermography – lock in and transient thermography.

Generally, specific applications for composite materials are related to: laminated composite structures reinforced with fibers (CFRP, GFRP), detection of defects in the repair of composite materials, evaluation of impact affected areas in composite structures, assessing areas around the holes, identification of surface defects, damages, coating quality and identification of thermo-physical properties of the inspected materials [7]. The basic setup of active thermography by reflection is presented in Fig. 1.

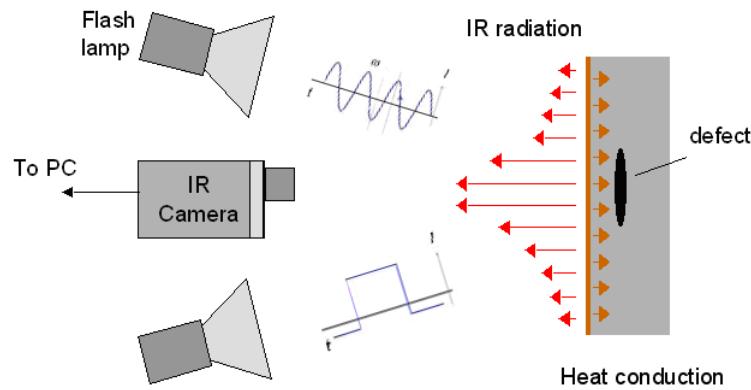


Fig. 1. The experimental setup for active thermography, by reflection technique.

Lock in thermography (LT) is based on creating heat waves on the surface of tested specimen. The sample is heated with a source creating a flux with a sinusoidal variation and with a given pulsation ω . When that wave is partly reflected by defects such as delaminations or inclusions, the reflected wave interferes with the incident one creating the appearance of interference patterns in the local distribution of the surface temperature. Then the temperature field is evaluated in terms of phase and amplitude using three main methods of analysis: *Harmonic approximation (frequency)* - HAF, *Harmonic approximation (time)* - HAT and *Single frequency DFT* - SF DFT, methods contained in the menu of the IR-NDT software, associated with an infrared (IR) camera.

In the application of the transient technique, also known as long pulse thermography, the surface under investigation is pulse heated. The time period of heating is of the order of several seconds, in contrast with that of milliseconds, in the case of short pulse or flash thermography, used for metallic items. The heating source consists in one or more powerful lamps and the resulting thermal transient field at the surface is monitored using an IR camera. The duration of the heating pulse depends on the thermal and physical properties of the materials, as well as

on its thickness. So, the heat flow into the sample is altered in the presence of a subsurface defect or feature, creating a temperature contrast at the surface easily to be detected in a thermogram obtained with the IR camera. Briefly, in transient thermography defects are detected because they affect the heat transmission across the component. In the case of the transient thermography, the menu of the IR-NDT software contains several methods of analysis: e-model, root –model and pulsed phase thermography model.

3. Experimental procedure

The integrated system aimed to perform active thermography contains an excitation source a (power electronics module and a panel with four halogen lamps). The power electronics module forms a functional unit with the IR-NDT software and IRX-box to control a connected lamp panel (actual power 2.6 kW). The IR-NDT package is advanced software containing various functions for easy, versatile use. The non-linear electrical signal for the modulation of the heat source is generated by IRX-box of the system. The modulation signal controls the power electronics and hence the power output of the heat source [8]. The Flir A 40 M camera uses an un-cooled micro-bolometer detector with a frame rate of maximum 50 Hz and a focal plane array (FPA) pixel format of 320(H) \times 240(V). This camera works in the spectral range 7.5-13 μ m and has a thermal resolution of 0.08°C [9].

The thermal properties of the material the two composite plates are made from carbon fiber reinforced plastic (CFRP) - are presented in table 1.

The basic properties involved in the NDI of a material are: k – thermal conductivity [W/mK], ρ – density [kg/m³] and c – specific heat capacity [J/kgK]. Other interesting thermal property are: $\alpha = k/\rho c$ – thermal diffusivity and $e = (kpc)^{1/2}$ – thermal effusivity. The thermal diffusivity is a measure of the material's ability to conduct heat versus its capacity to store it. The thermal effusivity measures the material's ability to exchange heat with its surroundings.

Table 1

CFRP thermal properties[4]

Material	k [W / mK]	ρ [kg / m ³]	c [J / kgK]	α [m^2 / s] $\times 10^{-7}$	e [$Ws^{1/2} / m^2 K$]
CFRP	7	1600	1200	36.5	3666

The specimen having irregularities of thickness variation type contains nine flat-bottom circular holes of different diameters at the same depth. The 400x180x3mm sample is presented in figure 2. The diameters of the holes are: $\Phi_1=\Phi_6=6$ mm, $\Phi_2=\Phi_7=20$ mm, $\Phi_3=18$ mm, $\Phi_4=\Phi_9=25$ mm, $\Phi_5=\Phi_8=12$ mm.

In this case, the examination was performed on the undamaged face of the plate.



Fig. 2. CFRP plate with defects (thickness variation)

The inspected object manufactured with internal flaws is shown in figure 3. This 300x300x2.5 mm composite plate includes some circular adhesive inserts during the manufacturing process, in order to simulate delaminations. The specimen has 10 layers with 0.25 mm thickness each. The inserts that simulates internal flaws 1 and 4 are located between layers 4 and 5 and one that simulates the defect 3 is located between layers 5 and 6. The position of internal defect 2 is between layers 8 and 9. The diameters of the internal defects are: $\Phi_1=25\text{mm}$, $\Phi_2=18\text{mm}$, $\Phi_3=20\text{mm}$, $\Phi_4=24\text{mm}$.

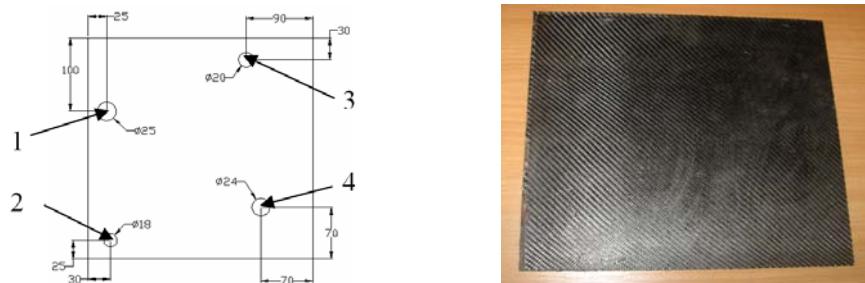


Fig. 3. CFRP plate with internal defects (delaminations)

The experimental setup is shown in Fig. 4.



Fig. 4. The experimental setup for inspecting the CFRP specimens

For the inspection with lock in method, the used parameters were: the excitation period – 25 [s], number of periods – 4 periods. The camera frequency image acquisition is 50 Hz, able to get 5000 images

The test parameters used during the transient long pulse inspection were: excitation period – 40 [s], duty cycle - 15 [%], amplitude low – 0 [%], amplitude high – 100 [%], acquisition duration 40 [s]. The camera frequency image acquisition is 50 Hz, easily to obtain 2000 images.

Experimental parameters have been chosen according to the material the inspected object was made of [9].

4. Experimental results

Using the presented software, which performs Fourier transform to obtain the amplitude and phase response to thermal heating of the selected frequency, it is possible to detect features of existing defects (size and location).

As IR-NDT program allows calculation of a series of parameters of the thermal field such as phase, amplitude, derivative (n), it could conduct to an assessment of the two methods used, taking into account several possible configurations.

Results obtained during inspection with lock in thermography are presented in Figs. 5-8. In the lock in method, the signal measured in each pixel is approximated by a second order polynomial function for the purpose of obtaining a uniform final image representation.

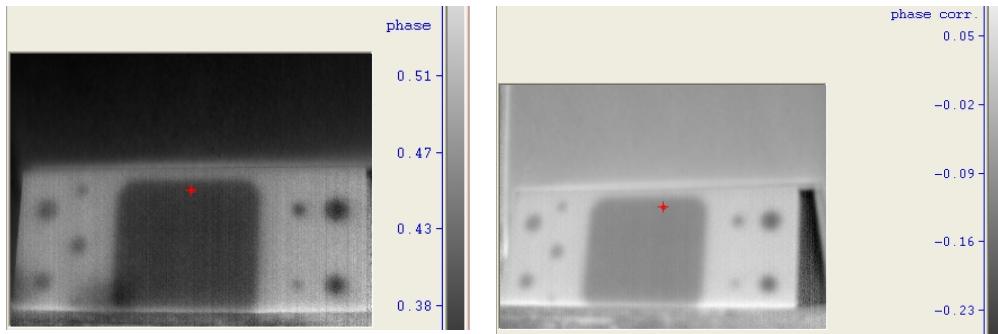


Fig. 5. Thermograms obtained with phase and phase correction using lock in inspection method, HAF analysis (left), SFDFT analysis (right)

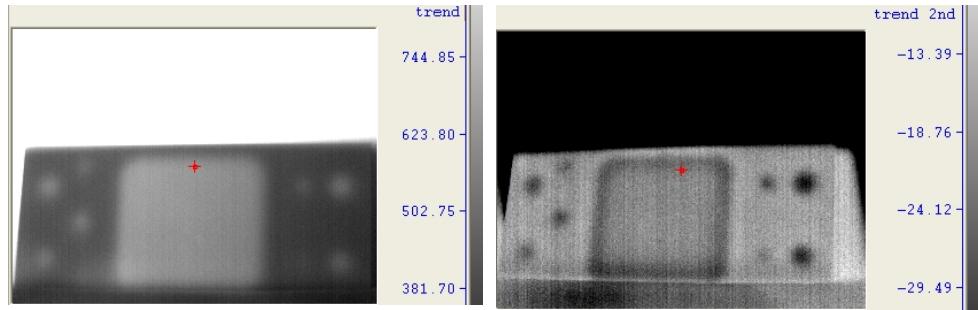


Fig. 6. Thermograms obtained with trend and second trend using lock in inspection method, HAF analysis (left), HAT analysis (right)

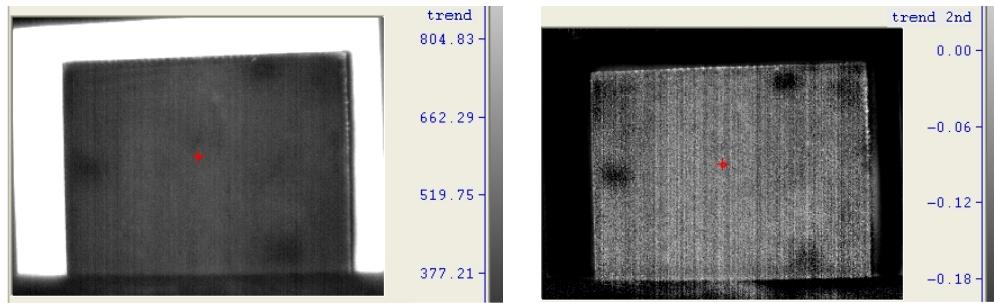


Fig. 7. Thermograms obtained with trend and second trend using lock in inspection method, HAF analysis (left), HAT analysis (right)

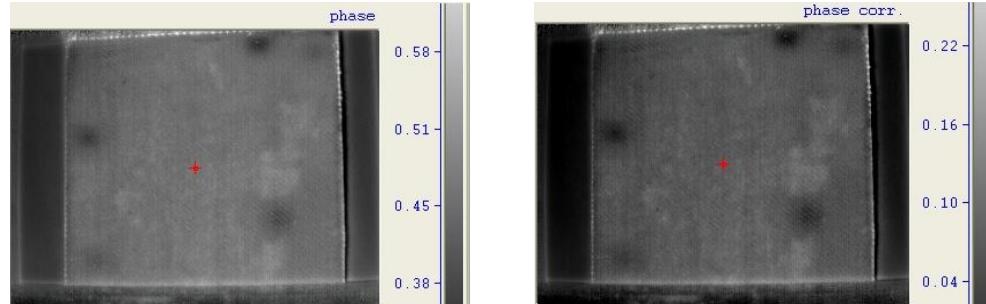


Fig. 8. Thermograms obtained with phase representation using lock in inspection method, HAF analysis (left), SFDFT analysis (right)

Representation of phase can be corrected by the software automated optimization, amplifying the final image contrast and reducing the phase jumps, thus leading to a uniform representation. Representations of trend and trend 2nd are in fact the thermograms obtained with the first and second derivative of the polynomial function that approximates the thermal behavior of each point.

The results of lock in inspection for CFRP plate with defects (thickness variation) are presented in table 2. Φ_{1-9} are the holes diameters for the first CFRP inspected plate (fig. 2), measured on the termograms obtained with four lock in configurations. The measures of the defects were made by reference to sample dimensions. The measurement procedure is the same in all cases.

Table 2
Results of lock in inspection for CFRP plate with defects (thickness variation)

Lock in configurations	Φ_1 [mm]	Φ_2 [mm]	Φ_3 [mm]	Φ_4 [mm]	Φ_5 [mm]	Φ_6 [mm]	Φ_7 [mm]	Φ_8 [mm]	Φ_9 [mm]
HAF analysis Phase representation	6.34	21.02	18.54	25.99	12.32	6.02	21.02	12.34	26.45
SFDFT analysis Phase correction representation	6.1	20.76	17.98	25.12	12.07	6.28	20.67	12.23	25.97
HAF analysis Trend representation	7.01	22.31	19.54	26.26	13.79	6.92	22.09	13.41	26.69
HAT analysis Trend 2 nd representation	6.54	21.23	18.76	25.27	13.51	6.47	21.32	12.93	26.25

In fig. 9 is presented a comparison between measured values on lock in termograms for the nine holes of the sample 1 and the dimensions of real defects.

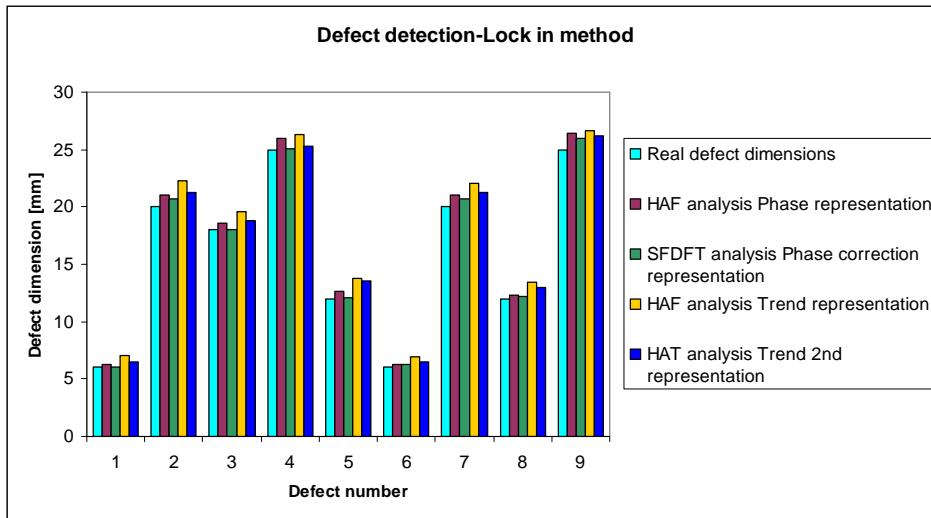


Fig. 9. Comparison between the results obtained with lock in configurations for CFRP plate with defects (thickness variation) and the dimensions of real defects

For the second plate (internal flaws) the measured values are presented in table 3. Φ_{1-4} are the internal defects diameters for the second CFRP inspected plate, measured on the termograms obtained with four lock in configurations.

Table 3
Results of lock in inspection for CFRP plate with internal defects (delaminations)

Lock in configurations	Φ_1 [mm]	Φ_2 [mm]	Φ_3 [mm]	Φ_4 [mm]
HAF analysis Phase representation	25.67	18.67	20.87	24.59
SFDFT analysis Phase correction representation	25.5	18.56	20.61	24.24
HAF analysis Trend representation	25.70	0	21.13	25.43
HAT analysis Trend 2 nd representation	25.63	0	23.9	24.19

In Fig. 10 is presented a comparison between measured values on lock in termograms for the internal flaws of the sample 2 and the dimensions of real defects.

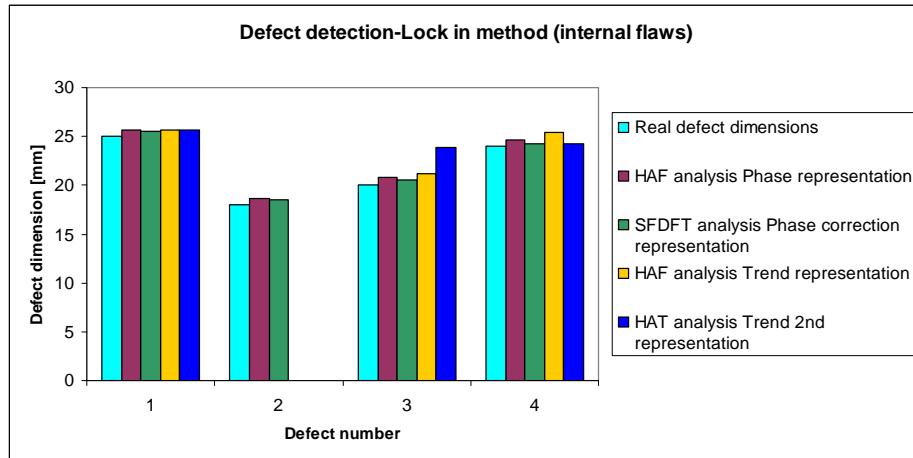


Fig. 10. Comparison between the results obtained with lock in configurations for CFRP plate with internal defects (delaminations) and the dimensions of real defects

Some thermograms obtained with transient method, in different representations, are presented in Figs. 11-13. The results obtained with this technique are based on the reconstruction of infrared images calculated with a polynomial function that approximates the thermal behaviour in each point. Polynomial function degree can be chosen between 2 and 5. Experiments were

performed with a third degree polynomial function, obtaining thus the representation of first and second derivative.

Residual representation consists in derivation of the recorded images and their reconstruction on this basis. The first derivative represents the change in the pixels along time axis. The same representation is then presented using the second derivative.

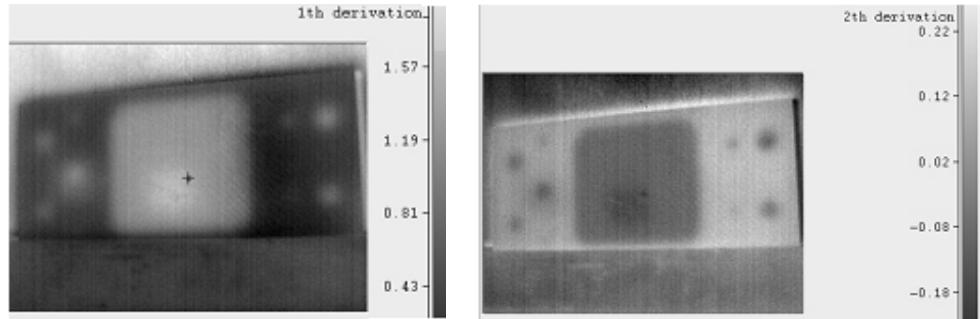


Fig. 11. Thermograms obtained with 1st and 2nd derivative using transient inspection method, root-model analysis

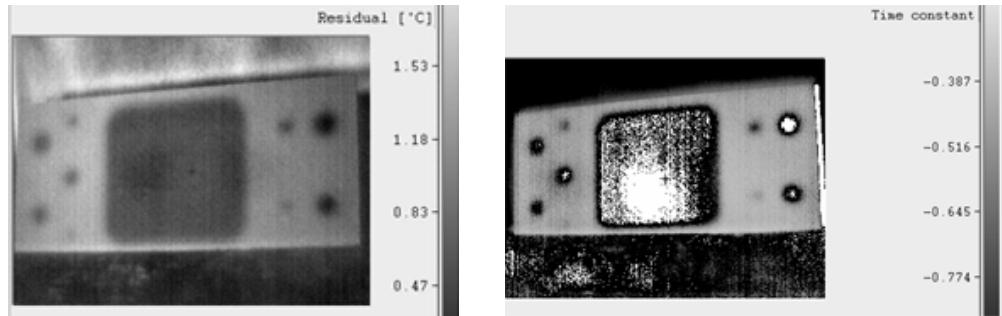


Fig. 12. Thermograms obtained with residual and time constant representation using transient inspection method, root-model analysis

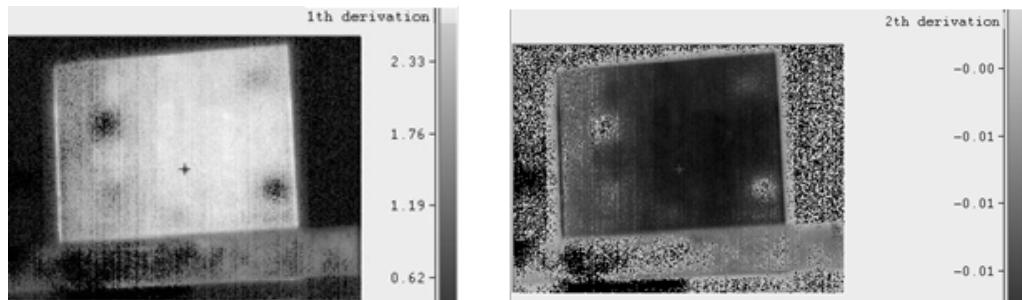


Fig. 13. Thermograms obtained with 1st and 2nd derivative using transient inspection method, root-model analysis

Transient measurements are sensitive to reflections and to material emissivity. The sensitivity of this infrared thermography method is also limited by the environmental thermal noise. Consequently, the inspected area needs to be surrounded by a curtain and/or measurement setup needs to be shielded against such disturbances. This technique has the advantage to retain the fidelity of the low frequency thermal event and highlights the signal contributed by a subsurface anomaly whilst suppressing high frequency of the non-thermal events [10].

The results of transient inspection for CFRP plate with defects (thickness variation) are presented in table 4.

Table 4

Results of transient inspection for CFRP plate with defects (thickness variation)

Transient configurations	Φ_1 [mm]	Φ_2 [mm]	Φ_3 [mm]	Φ_4 [mm]	Φ_5 [mm]	Φ_6 [mm]	Φ_7 [mm]	Φ_8 [mm]	Φ_9 [mm]
Root-model analysis 1 st derivative representation	7.93	22.78	21.34	25.00	15.61	7.13	22.75	15.38	26.97
Root-model analysis 2 nd derivative representation	6.57	21.54	20.13	23.36	14.19	6.97	21.34	13.95	26.09
Root-model analysis Residual representation	6.78	21.93	20.81	23.74	14.92	7.51	21.91	14.19	26.46
Root-model analysis Time constant representation	6.97	22.14	21.18	24.21	15.17	7.23	22.16	15.06	26.83

In Fig. 14 is presented a comparison between measured values on lock in termograms for the nine holes of the sample 1 and the dimensions of real defects.

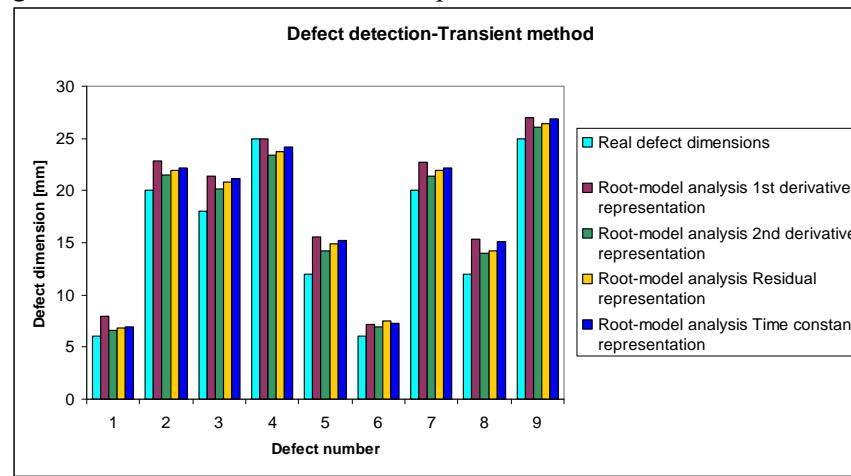


Fig. 14. Comparison between the results obtained with transient configurations for CFRP plate with defects (thickness variation) and the dimensions of real defects

For the second plate (internal flaws) the measured values on termograms obtained with transient method configurations are presented in table 5.

Table 5

Results of transient inspection for CFRP plate with internal defects (delaminations)

Lock in configuration	Φ_1 [mm]	Φ_2 [mm]	Φ_3 [mm]	Φ_4 [mm]
Root-model analysis 1 st derivative representation	26.58	21.98	21.90	24.76
Root-model analysis 2 nd derivative representation	25.87	21.35	21.06	24.20

In Fig. 15 is presented a comparison between measured values on transient termograms for the internal flaws of the sample 2 and the dimensions of real defects.

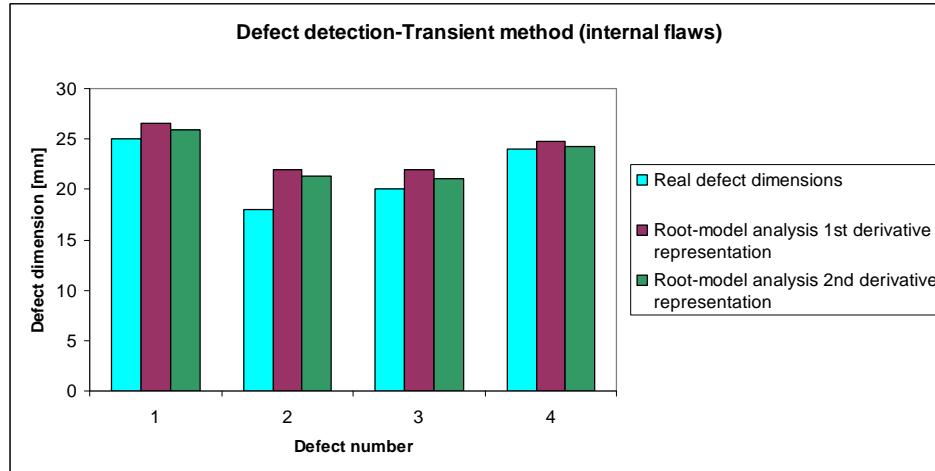


Fig. 15. Comparison between the results obtained with transient configurations for CFRP plate with internal defects (delaminations) and the dimensions of real defects

In Figs. 16 and 17 are presented the comparisons between the dimensions of real defects and the best results obtained with transient and lock in methods.

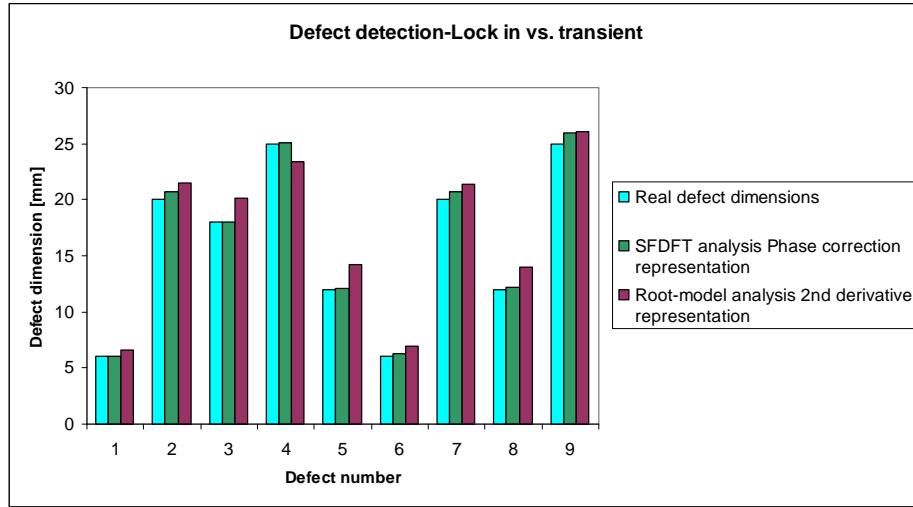


Fig. 16. Comparison between the dimensions of real defects and results of lock in and transient inspection methods for CFRP plate with defects (thickness variation)

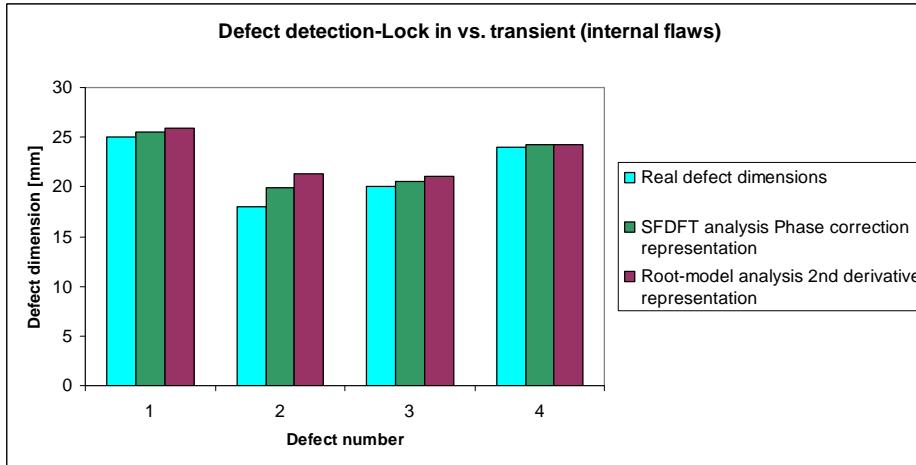


Fig. 17. Comparison between the dimensions of real defects and results of lock in and transient methods for CFRP plate with internal defects (delaminations)

Experimental parameters were chosen after performing several tests, with variations in the duration and number of periods, in the camera frequency, from the results presented being retained the values allowing to obtain the most conclusive thermograms (the best contrast).

All presented images were chosen to be representative for all captured ones, in terms of the highest temperature differences on the surface of tested CFRP specimens.

5. Conclusions

The experiments were intended to detect two types of defects - thickness variation and delaminations – existing in CFRP plates. Two active IRT methods were used for the inspection - the lock in method and the transient method, in order to determine which one offers better results when the main parameters of each are handled in the available range of temperature -10°C to 55°C. The IR-NDT software allows the calculation of a series of attributes for evaluation: phase, amplitude, derivative (n), and make possible an assessment of the two methods, in all possible configurations.

The main conclusion resulting from the completion of experiments is that using both active methods, the best results in terms of defect size were obtained using lock in method, SFDFT analysis (phase correction representation) for the two types of inspected defects.

Further research work is necessary to demonstrate the capabilities of the IR-NDT software and of the presented NDT setup for getting a more refined characterization of such defects.

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R E F E R E N C E S

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