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Signal to noise ratio (SNR) comparison for lock-in thermographic data processing methods in CFRP specimen

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Abstract

In this paper, the use of a signal to noise ratio is proposed for the quantification of the goodness of two selected lock-in thermography processing techniques. The single Fourier Transform (DFT) and the Harmonic Approximation (HA) were applied to experimental data from a CFRP specimen containing 25 defects (Teflon® inclusions) at different depths and having several sizes. The obtained phase images were compared using this SNR parameter value, and DFT showed better results than HA, for which a reduction of approximately 6dB was quantified. This reduction affects consideraly the automated detection capabilities of smaller and depper defects, for which a SNR value higher than one (0 dB) is required.

1. Introduction

Active infrared thermography applied to the non-destructive testing (NDT) of materials offers a reliable, straightforward and fast means for retrieving structural information from a specimen. In the lock-in technique, which is also known as thermal wave imaging, the heat introduction occurs periodically with a certain frequency, and the local surface temperature modulation is evaluated for the detection of anomalies that could indicate the presence of a defect or inhomogeneity. The temporal evolution of the surface temperature is stored in a thermographic images sequence (thermograms). Defect enhancement techniques must be applied in order to produce a successful thermal inspection. Two specific image processing techniques, one based on the Discrete Fourier Transform (DFT) and the other based in the Harmonic Approximation (HA) of the Fourier Transform [1-2], have been applied to lock-in thermographic inspection showing both advantages and disadvantages. The present work describes how to quantify the goodness of each technique in defect detection using a signal to noise ratio (SNR). The performance of the proposed method has been evaluated on a carbon fibre reinforced plastic (CFRP) specimen containing several defects, having different surface geometries, and being subjected to a sinusoidal excitation. This evaluation is done for sequences obtained with different excitation frequencies.

2. Basic principles of the selected processing techniques

2.1. DTF based algorithm

The Discrete Fourier Transform (DFT) is a technique that allows a domain change from time to frequency by means of the following expression:

$$f_j = \sum_{k=0}^{N-1} x_k \cdot e^{-\frac{2\cdot\pi\cdot i}{N} jk} = Re_j + i \cdot Im_j \quad j = 0,...,n-1 \tag{1}$$

where *j* values are the frequency increments and *Re* and *Im* are respectively the real and imaginary parts of the DFT, from which it is possible to get the amplitude and phase components:

$$A_j = \sqrt{Re_j^2 + Im_j^2} \tag{2.1}$$

$$\phi_j = a\tan\left(\frac{Im_j}{Re_j}\right) \tag{2.2}$$

Considering this, if we have an image sequence with the temporal evolution of the surface temperature of a specimen, we can apply the DFT to the evolution of each pixel in order to get two new sequences with the amplitude and phase images.

From all this information, the related with the excitation frequency is selected so finally we have only one phase image and one amplitude image. This component of interest is calculated considering the window size and the number of entire periods of the sinusoidal signal that enter in that window.

2.2. Harmonic Approximation based algorithm

The Harmonic Approximation (HA) is an approximation of the Fourier Transform (FT) based on the idea that only four (or even three) data points per modulation cycle provide the correct phase and also the amplitude of a sine signal. Though more data points reduce the noise, the following discussion will concentrate on four equidistant signal data points, S_1 to S_4, which are used to obtain the amplitude (A) and phase shift (Φ) values with respect to a given reference modulation:

$$A = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2} \tag{3.1}$$

$$\phi = \operatorname{atan}\left(\frac{S_1 - S_3}{S_2 - S_4}\right) \tag{3.2}$$

Therefore, as well as FT based processing method, the Harmonic Approximation based algorithm also affords two images from the original thermographic sequence, a phase image and an amplitude image. The reference modulation signal (figure 1, above) is provided by the sinusoidal illumination used as excitation source in the lock-in thermography experiment or simulation, and, for each pixel (figure 1, below), S_1 to S_4 are the radiation values in the four selected images.

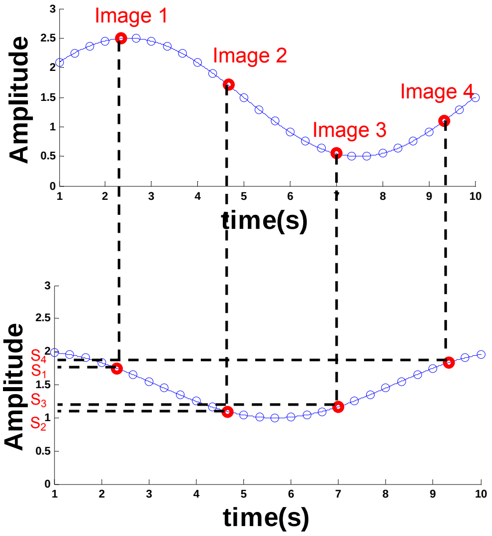

Fig. 1: Images selection during harmonic approximation processing algorithm.

3. Signal to noise ratio (SNR) quantification

A SNR value [3] is used to determine what processing algorithm is more suitable for a certain application, based on the following requirement: to provide enough thermal contrast between defective and non defective areas, so the automatic detection of a particular kind of defect could be possible, for which a SNR value higher than 0dB must be guaranteed. To determine this SNR value, in the phase image obtained with the processing algorithm, two areas are selected: an area inside a defect and an area around it (sound area), as it is shown in figure 2. For each area the medium phase value is calculated. As mentioned, in order to detect the defects it is necessary to have enough thermal contrast between a defect and its surroundings. Because of that, the defective area is considered as “signal” (*Sarea*) and the area around it as “noise” (*Narea*) so that the SNR is calculated as it is defined in Eq.4, where σ is the standard deviation of the noise.

$$SNR_1 = \frac{S}{N} = 20 \cdot \log_{10}\left(\frac{abs(Sarea_{Average} - Narea_{average})}{\sigma}\right) \quad [dB] \qquad (4)$$

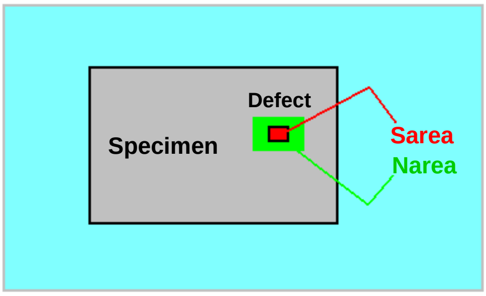

Fig. 2: Areas selection for SNR calculation

The proposed method for calculating the S/N ratio is defined to measure the quality of image constrast for TV transmision systems and it is independent of how the defects appear, that is, the defect could be cooler or heater than the surroundings and the result shouldn't change.

4. Experimental setup and results

An CFRP specimen was tested in reflection mode using a sinusoidal heat source (2kW), long time window to avoid the heating transient effect, and recording three periods of the signal. The surface heating proccess was recorded with a medium wave IR camera at several excitation frequencies. The experimental setup can be seen schematically in figure 3. The Specimen contained a total of 25 Teflon® square inclusions of five lateral sizes (3, 5, 7, 10 and 15 mm) grouped into five depths (0.2, 0.4, 0.6, 0.8 and 1 mm), as is shown in figure 4.

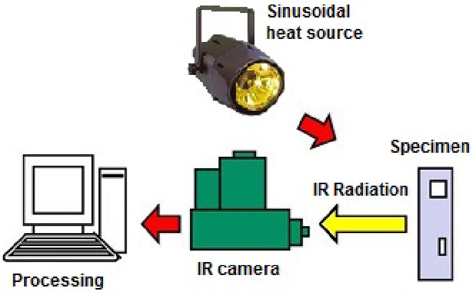

Fig. 3: Schematic of the experimental setup

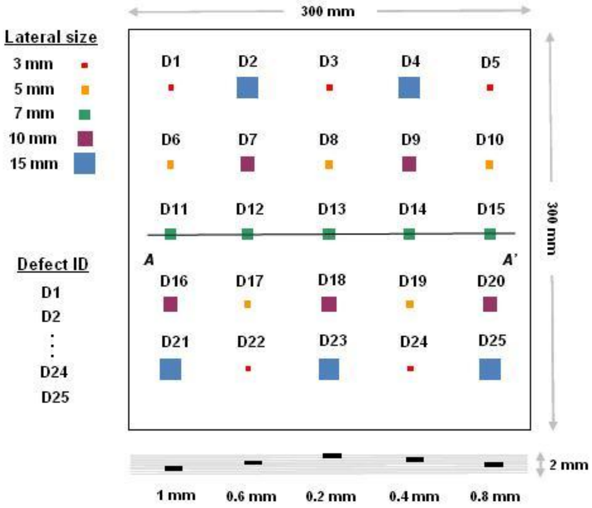

Fig. 4: Distribution of defects in the CFRP specimen

Three thermographic sequences were obtained at different excitation frequencies (10, 5 and 3 mHz), and these were processed with both Fourier Transform and Harmonic Approximation algorithms. The resulting phase images obtained with Eq.(2.2) and Eq.(3.2), are shown in figures 5 to 7. The SNR values for each case are provided in table 1.

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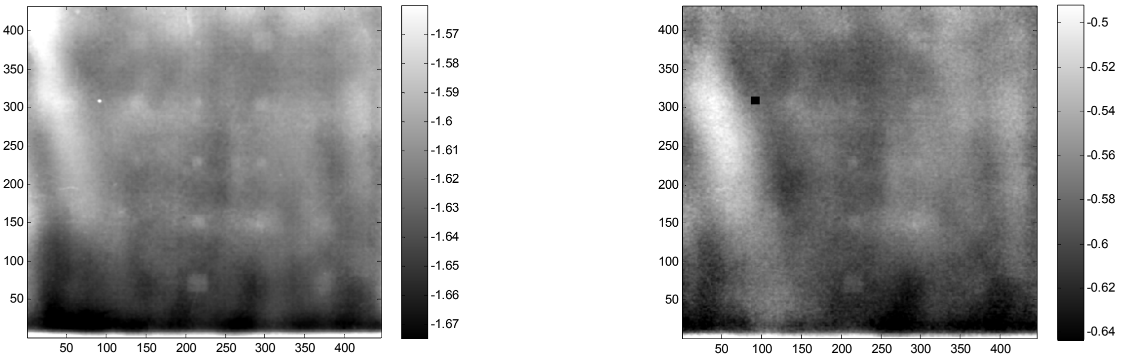
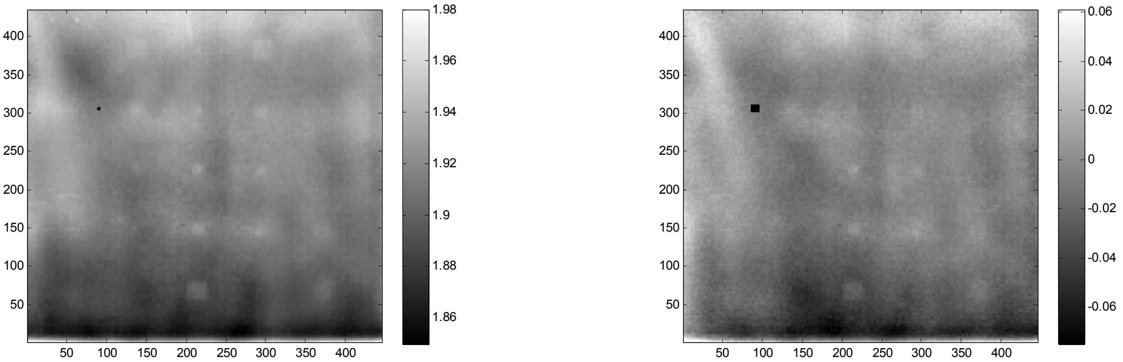


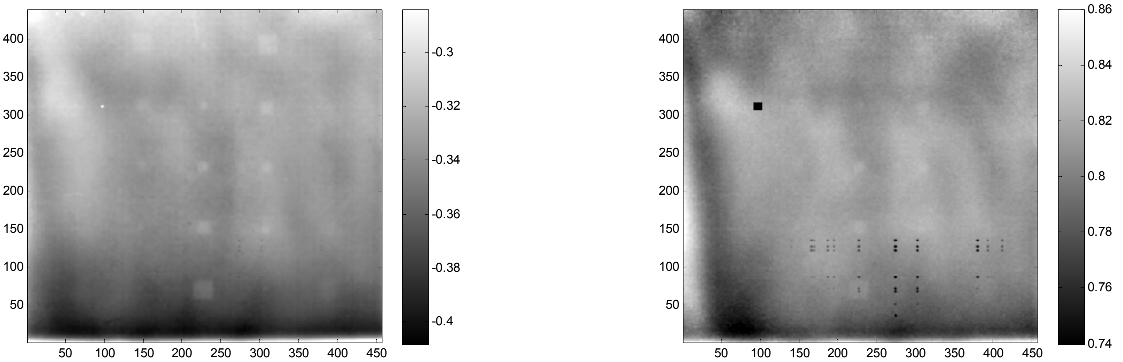
(a) (b)

Fig. 5: Resulting phase images from both (a) Fourier transform and (b) Harmonic Approximation algorithms applied to sequence 1 (Excitation frequency = 10mHz).



(a) (b)

Fig. 6: Resulting phase images from both (a) Fourier transform and (b) Harmonic Approximation algorithms applied to sequence 2 (Excitation frequency = 5mHz).



(a) (b)

Fig. 7: Resulting phase images from both (a) Fourier transform and (b) Harmonic Approximation algorithms applied to sequence 3 (Excitation frequency = 3mHz).

In the phase images it can be observed that some defects are not detected. In this cases it is indicated in table 1 by the “ND” acronym, which means “non detected”. The scale of each image has been adjusted in order to see the maximum number of defects. However, it can be observed that a non uniform heating, non corrected by the phase, is present in all the cases. In the raw image sequences it can be observed that the heating source is not centered and it causes that some parts of the specimen reach a higher temperature than others, depending on the experiment: for sequence 1 (f=10mHz) and 2 (f=5mHz) the source is centered top right,and for sequence 3 (f=3mHz) it is in the bottom right. An example is shown in figure 8, where the temporal temperature evolution of two pixels corresponding to non defective areas, one of the top of the specimen and the other of the bottom, are represented. The differences in the amplitudes of the sinusoidal evolutions can be observed.

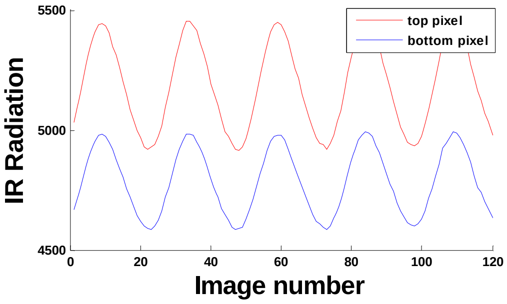


Fig. 8: Temporal temperature evolution of one pixel at the top of the specimen and other at the bottom.

Besides, it can be observe that there are some defective pixels (known as badpixels) in all the images, whose influence increases with the HA processing technique.

From the experimental results can be drawn the following conclusions. Firstly, it can be observed that in all the cases Discrete Fourier Transform procesing algorithm provides better results than the Harmonic Approximation one. This is logical since HA is an approximation of the DFT. SNR values for HA suffer an average degradation of 6dB approximately. Besides, results are better in general for the lowest excitation frequency (f=3mHz).

It was mentioned that automatic detection of defects demans a SNR value higher than 0dB. However, we can visualy detect defects with a lower SNR through the employed processing techniques and doing an adequate scaling in the obtained images.

Regarding the size and depth of the defects, we can say that the more superficial a defect is, the easier is detected, and the same happend with the size, the bigger a defect is, the easier detected. Nevertheless, the aforementioned non uniform heating influence the results making that, in some cases, the opposite occurs, as happens with defects 4 and 23 of sequence 3, both of the same size at different depths, being better detected the most deep. None of the deepest defects (depth=1mm) have been detected, and only the biggest ones of the following deeper (depth=0.8mm) are detected (sizes=15 and 10 mm).

5. Conclusions

The performance of two different processing algorithms applied to modulated thermography have been quantificated using a SNR parameter value. An CFRP specimen has been excited using modulated light with different frecuencies and the resulting thermographic sequences were processed with both algorithms, DFT and HA. As a result, two phase images were obtained for each experiment and compared using a SNR parameter value, as defined to measure the quality of image constrast for TV transmision systems.The automatic detection of defects requires the SNR value to be higher than 0dB. The obtained SNR values show that, as was expected, DFT algorithm provides better results than HA. A reduction of approximately 6dB has been quantified when the HA algorithm is used to process the thermography sequence. This reduction affects consideraly to the automated detection capabilities of smaller and depper defects when the HA is used.

The more superficial and bigger is a defect, the better detected is. However, in our experiments the heating source was not well centered in the specimen surface, and it caused a non uniform heating that afects the measurements, making that, in some cases, the opposite occurs. Finally, it is observed that the best results are obtained for the lowest excitation frequency.

Table 1. *SNR values for each defect with both processing techniques*

			Sequence 3 (f=3mHz)		Sequence 2 (f=5mHz)		Sequence 1 (f=10mHz)	
			DFT	HA	DFT	HA	DFT	HA
Defect	Size (mm)	Depth(mm)	SNR (dB)	SNR (dB)	SNR (dB)	SNR (dB)	SNR (dB)	SNR (dB)
23	15	0,2	2,8672	-2,1149	5,6896	1,3601	4,8505	-2,799
4	15	0,4	4,9114	-1,8722	-6,0605	-8,9551	-5,9005	ND
2	15	0,6	-2,0902	ND	-8,5807	ND	-10,997	ND
25	15	0,8	-9,0305	ND	1,0431	-3,0972	0,4115	ND
21	15	1	ND	ND	ND	ND	ND	ND
18	10	0,2	8,7797	0,904	6,7119	2,7268	6,8433	-0,9274
9	10	0,4	9,8878	0,4164	1,1577	-5,8243	-2,0633	-6,5331
7	10	0,6	2,4159	ND	1,0642	ND	0,5909	ND
20	10	0,8	-3,0882	ND	2,0381	-3,3551	ND	ND
16	10	1	ND	ND	ND	ND	ND	ND
13	7	0,2	4,9724	-3,5463	5,9674	4,4135	5,6719	0,1888
14	7	0,4	9,7732	3,3034	8,1233	0,5189	6,4123	-4,7721
12	7	0,6	-4,9203	ND	ND	ND	ND	ND
15	7	0,8	ND	ND	ND	ND	ND	ND
11	7	1	ND	ND	ND	ND	ND	ND
8	5	0,2	10,3073	0,9035	-1,4075	ND	-0,1058	-9,6294
19	5	0,4	8,9383	2,4795	4,926	0,7169	4,5179	ND
17	5	0,6	ND	ND	ND	ND	ND	ND
10	5	0,8	ND	ND	ND	ND	ND	ND
6	5	1	ND	ND	ND	ND	ND	ND
3	3	0,2	1,4798	ND	-27,5524	ND	-22,3677	ND
24	3	0,4	ND	ND	ND	ND	ND	ND
22	3	0,6	ND	ND	ND	ND	ND	ND
5	3	0,8	ND	ND	ND	ND	ND	ND
1	3	1	ND	ND	ND	ND	ND	ND

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