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THERMOELASTIC SIGNAL PROCESSING USING AN FFT LOCK-IN BASED ALGORITHM ON EXTENDED SAMPLED DATA

L. D'Acquisto [1], *A. Normanno, G. Pitarresi* [1], *A. M. Siddiolo* [2]

[1] Dipartimento di Meccanica, Università degli Studi di Palermo, Palermo, Italy, dacquisto@dima.unipa.it
[2] siddiolo@gmail.com

Abstract – A fast infrared scanner is used to acquire the thermoelastic effect induced temperature changes along a line on the surface of cyclically loaded tensile samples. The raster scanning movement of the single detector allows the sampling of temperature versus time. This data are then post-processed by means of a lock-in algorithm coupled with 1D and 2D FFT analyses in order to filter out the thermoelastic signal from the noisy measured signal. A data extension algorithm is proposed which uses the information from different acquired frames to extend the data sampling window. The whole signal processing setup is evaluated on experimental data with successful results, proposing a potential tool for low cost Thermoelastic Stress Analysis.

Keywords: Thermoelastic Stress Analysis, Lock-In, FFT analysis.

1. INTRODUCTION

Among NDE techniques nowadays used to investigate loaded elements, thermoelastic stress analysis has become a well-established technique to measure the full-field stress distribution of components under cyclic load [1]. Thermoelastic Stress Analysis techniques (TSA) perform this investigation by measuring temperature changes on the surface of bodies when simple thermoelastic laws apply [2].

The Thermoelastic Effect describes the temperature changes in loaded matter as induced by the volume changes under linear elastic behaviour. When such transformation is adiabatic and the material is homogenous and isotropic, a simple linear relationship can be derived where the temperature change, measured on the free surface of a body, is proportional to the first stress invariant as follows:

$$\Delta T = -T_o \cdot K \cdot \Delta\left(\sigma_x + \sigma_y\right) \quad \text{with} \quad K = \alpha / \rho C_p \qquad (1)$$

where T_o is the absolute temperature, K the thermoelastic constant function of the coefficient of thermal linear expansion α the density ρ and the specific heat C_p.

In order to detect very small temperature changes (about 0.1 K in steel stressed at 100 MPa), thermoelastic stress measurements require suitable equipment; this is usually obtained by means of highly sensitive infrared detectors and a lock-in amplifier able to detect that part of the temperature signal that is coherent with the load, i.e. the thermoelastic signal. Cyclically varying loads are also routinely applied in order to achieve adiabatic conditions able to freeze the peak to peak amplitude of the thermoelastic effect induced temperature change, which is then modulated according with loading cycle. General practise of these techniques is usually carried on by means of on purpose developed commercial hardware, with most modern IR thermocameras using focal plane array detectors able to provide full-field maps of the thermoelastic signal in few seconds. While such tools are so far available at elevated costs and with a limited choice of suppliers and configurations, the present work employs a methodology using low cost IR scanners to measure the thermoelastic signal [3,4]. A data extension algorithm able to extend the sampling window is in particular presented and applied together with 1D and 2D FFT based lock-in procedures to optimise the signal filtering operations for the evaluation of the thermoelastic signal.

2. EXPERIMENTAL SETUP

In this work a low resolution termocamera (NETD=0.12 K) Varioscan 3022 by Jenoptik GmbH was used. This system employs a single thermoelectrically cooled MCT IR detector assisted with two rotating mirrors collecting the signal horizontal-wise and vertical-wise on a full field frame array of 360×240 pixels.

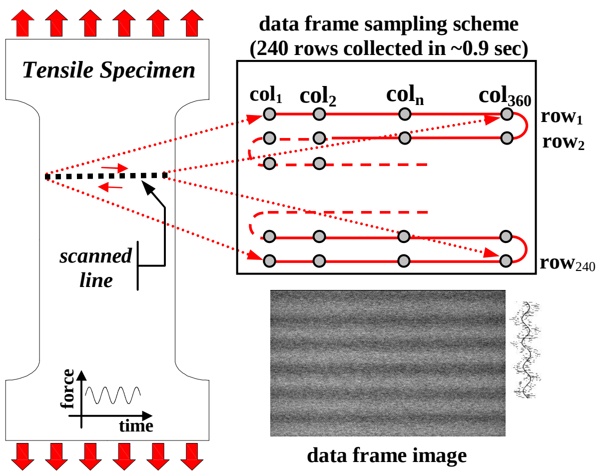


Fig. 1. Scheme showing the line scanning sampling mechanism and a data frame image at 6 Hz sine loading.

When data acquisition is performed as *line scan*, a line along the surface under investigation is repeatedly raster scanned into 360 points acquired in 1/270 s. A single thermogram is then obtained as a data frame array by piling up 240 rows consecutively acquired from the same line.

The temperature from a pixel on the scanned line is acquired periodically whenever the optical path of the sensor focuses on it. The information from one pixel location is then stored in a column of the data frame array. The column-wise information is then a measure of temperature versus time on the same point of the sample surface. This enables a procedure by which the temperature-time variation is sampled over 360 aligned points for a total time of 0.9 s (i.e. the frame rate). If the body is loaded at sufficiently slow frequencies, the thermoelastic effect induced temperature change can be sampled over a finite number of periods during a single frame acquisition. A scheme of this sampling mechanism for a uniform stress field generated in a tensile sample is given in Fig. 1. It is possible to distinguish greyscale horizontal fringes determined by the thermoelastic effect periodically induced temperature changes due to cyclic loading frequency f_L on the specimen under loading. A simple relationship can be established between the number of horizontal thermal fringes shown in one frame, n_S, and the camera frame rate f_R:

$$n_S = f_L / f_R = f_L \cdot (0.888\,s) \qquad (2)$$

where 0.888 *s* is the exact time spent by the camera employed in this work to acquire a frame. The time shift on the thermoelastic signal between different columns is negligible given the high speed of the sensor line swap.

3. DATA PROCESSING

The data processing approach adopted in this work for an effective recovery of the measurement information conveyed by the noisy temperature signal relies on a preliminary processing of grabbed thermograms for data enhancement and on signal processing using 1D or 2D FFT lock-in based algorithms.

The data enhancement procedure applied in this paper follows a time domain approach, aiming at obtaining, from several consecutive acquired set of thermograms, a sample of data containing a greater number of periods of the fringe pattern described.

On purpose developed commercial thermocameras implementing lock-in signal analysis techniques use lock-in amplifiers to detect and measure very small AC signals deeply buried in noise. Lock-in amplification is traditionally accomplished with expensive, monolithic hardware that requires a frequency reference. Typically, an experiment is excited at a fixed frequency (from an oscillator or function generator), and the lock-in detects the response from the experiment at the reference frequency. In the general case, the input consists of signal plus noise. Noise is represented as varying signals at all frequencies. The ideal lock-in only responds to noise at the reference frequency. Noise at other frequencies is removed by the low pass filter following the *mixer* (see Fig. 2).

Actually, engineers and scientists are going beyond what traditional black-box DSP implementations can do by defining the hardware functionality in software to create virtual instrumentation [5]. In this work, a peculiar lock-in software procedure was set up using low-cost computer-based technologies for accurate measurement of the thermoelastic temperature change under cyclic loading, by means of a standard thermocamera.

In this work a self-referenced lock-in data processing technique was developed, in which the reference signal was directly obtained from spectral filtering of the global temperature signal (*S* in Fig. 2). Once the main carrier frequency is extracted from the raw data, this is then used to build a noiseless reference carrier signal modulated with the obtained reference frequency. The extraction of a reference signal as described above will enable to perform the analysis without using any external loading signal (this possibility is also shown in the scheme of Fig. 2 with the dotted line link). As shown in Fig. 2 the core of the lock-in technique consists in mixing the measured signal, named S_T, with the reference signal which is a carrier of the loading frequency ω_R, i.e. the useful frequency.

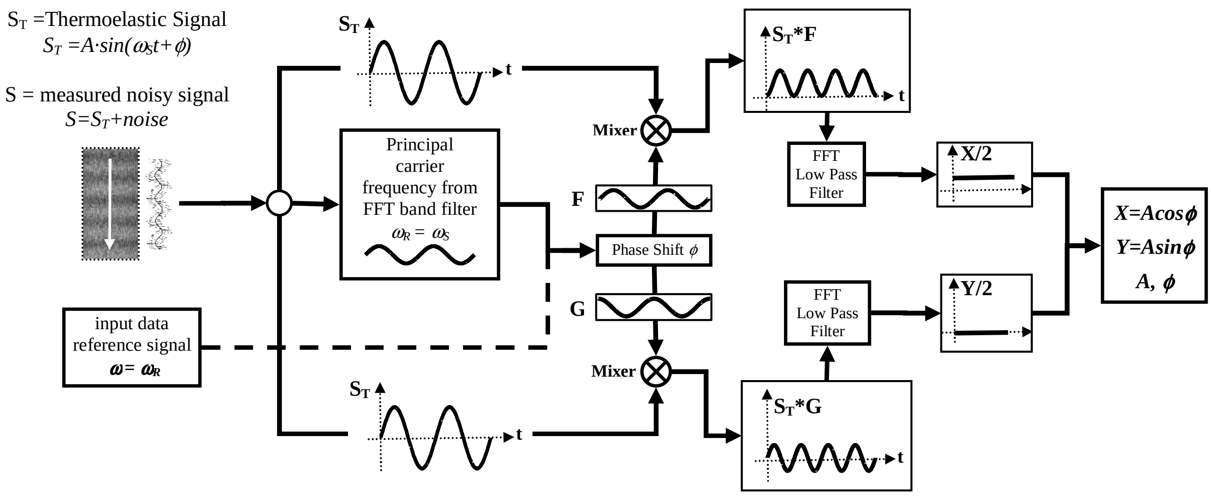


Fig. 2. Schematic representation of the lock-in signal processing.

Once the loading frequency ω_R is obtained, two pure cyclic reference signals named F and G, with F in quadrature with G, are built and multiplied to S (for simplicity diagrams shown in Fig. 2 perform this operation on the clean thermoelastic harmonic component S_{T}). This operation results in two signals which contain the information of interest as DC signals, and hence a low-pass filtering operation performed with FFT analysis is able to filter out such components named X and Y. These represent the thermoelastic signal components in phase and in quadrature with the reference signal; by combining them the thermoelastic signal amplitude A is readily obtained.

The above procedure is implemented in this work with an algorithm using the Fast Fourier Transform functions available in Matlab®. The approach here proposed implements a 1D FFT analysis on each column of the data frame array, and results are also compared with a previously implemented 2D FFT approach proposed in [4]. This 1D lock-in treatment allows the thermoelastic signal to be derived on each scanned point independently, enabling its immediate application to the case of a 2D stress field analysis. In fact although the 2D FFT based treatment from [4] is believed to be more effective in noise rejection, it is more elaborate for analyzing 2D stress fields.

A key issue influencing significantly the signal quality of the lock-in processed thermograms is the frequency resolution of the FFT Low Pass Filters employed as shown in Fig. 2. The peculiar features of the frame grabbing of the thermograms, due to the uneven time shift between odd and even rows of the acquired thermogram (see Fig. 1), do not satisfy the basic condition that the sampled data are equally spaced in time, required to apply FFT analysis. As a consequence of this available data are halved, by considering only the even rows or the odd rows from a thermogram acquired as *line scan*.

Within each thermogram the total number of rows is then reduced from 240 to 120. The corresponding time interval Δt becomes equal to one oscillation period of the mirror, i.e. Δt=2·(1/270) s; then f_s =1/Δt=135 Hz is sampling frequency. The maximum loading frequency applicable for the FFT analysis to work, i.e. the Nyquist frequency, will be half the sampling frequency, $f_{Ny}=f_s/2$=67.5 Hz.

Usually in TSA the thermoelastic signal is significantly corrupted by noise and then a reduced number of points from a single frame (as in the setup here adopted), cannot be adequate to perform effectively the filtering operations based on FFT which are shown in Fig.2. A simple averaging over time of several subsequently acquired frames has not been considered because it would reduce the noise by narrowing the bandwidth, i.e. gaining improved noise rejection but worsening time response.

It is otherwise plain that if the total sampling period were extended, a higher n_s value and a higher frequency resolution would be obtained. This would also gain smaller influences of border effects and a more effective noise to signal reduction. A sample data extension would represent an improvement in data signal processing collection, enhancing the quality of both 1D and 2D-FFT filtered results.

The data enhancement technique proposed in this work, for the measurement of the thermoelastic signal on cyclically loaded elements, is based on a data extension procedure performed in the time domain. A custom synchronization algorithm to stick together several acquired thermoelastic frames is therefore proposed to obtain sample data over a time window longer than a single frame.

There is however a small time gap between two subsequent frames during which the thermocamera is not acquiring the signal. So if these are joined by simply appending one after the other, a discontinuity is then inserted in the temperature versus time data of the new array at the point of attachment of the two original frames, introducing further noise which can affect the analysis.

The algorithm proposed in this work overcomes this problem by means of an iterative procedure. Two subsequently acquired frames are tentatively spliced and then analysed by FFT, by iteratively removing one more line from the beginning of the second frame before joining the two frames. All performed trials of joining the two subsequent frames are evaluated by comparing their amplitude spectra; the tentative joining operation which shows the highest peak in amplitude spectrum at the loading frequency ω_R is chosen as the best joining of the two frames. This is illustrated in Fig.3 where four tentative joining operations are shown, together with their amplitude spectra. The third case is the optimal because it shows the highest amplitude peak at exactly the loading frequency of the sample (3,38 Hz).

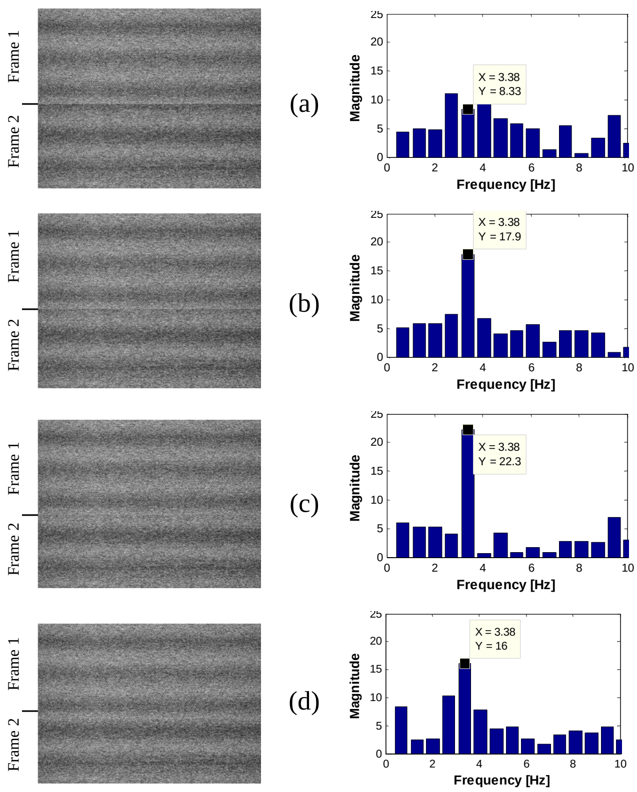


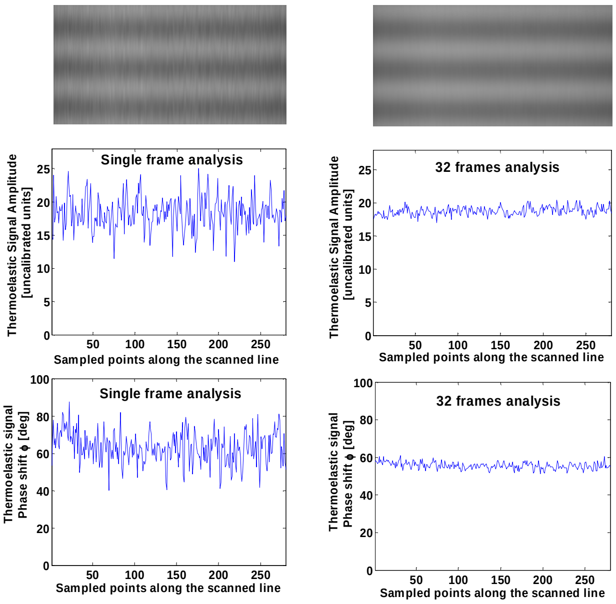
Fig. 3. Different splice of the same pair of thermoelastic frames (R= 3,38 Hz) - a) simple queuing of the two frames, rejected splice; b) and d) rejected splices; c) optimal splice.

4. RESULTS

Polycarbonate tensile samples undergoing sinusoidal load have been investigated by recording the temperature signal at different traction-traction load amplitudes. An average load of 2500 N was applied, with a peak-to peak load amplitude ranging from 750 to 2250 N.

Two principal aspects of the proposed thermoelastic signal processing have been taken into account to evaluate experimental results: a) the synergic enhancement effect produced by the data extension procedure and the FFT lock-in based algorithm, b) the different filtering effectiveness of the 1D FFT and 2D FFT algorithms.

Fourier Transform is usually applied in column-wise order on the array of pixels containing the fringe pattern irradiance: this is referred to as 1D-Fourier Transform.



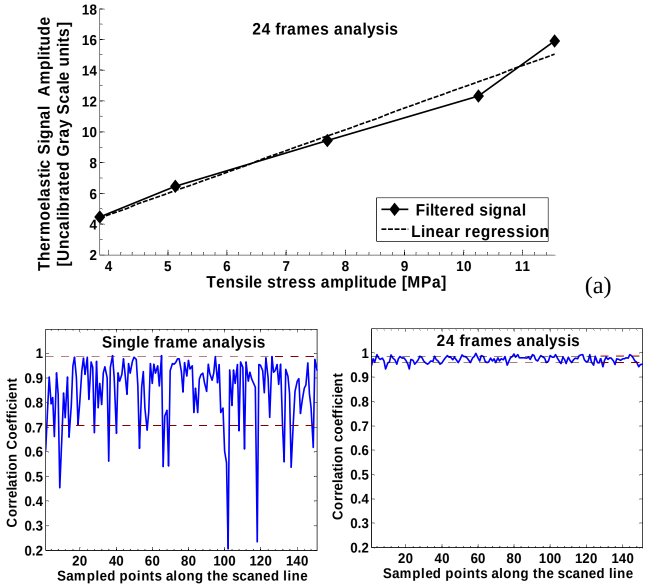
(a) (b)

Fig. 4. Processed temperature data from a tensile sample loaded at about 3.4 Hz. Thermoelastic signal amplitude and angular phase shift (from reference signal) for: a) a single frame, and b) 32 joined frames.

A thermogram recorded on the sample specimen, column-wise processed by means of the proposed 1D-FFT lock-in algorithm is shown on top of Fig. 4a. Due to the limited extension of the data set, efficiency of the 1D-FFT based lock-in filtering algorithm is not at its best and an appreciable noisy pattern is still present. This is observed in the plots at the bottom of Fig. 4a that show the amplitude A and phase ϕ of the thermoelastic signal, along all columns in the frame.

Data processing of extended temperature sample data from the same tensile specimen was performed on several joined data frames. Plots in Fig. 4b show the results for 32 joined data frames, evidencing an improvement in the quality of the thermoelastic signal, if compared to results shown in Fig. 4a. This confirms the positive synergic effect of combining the 1D-FFT lock-in filtering and the data extension procedure.

The above illustrated improvement in the quality of the thermoelastic signal, processed as proposed in this paper, is also confirmed by the improvement in the linear correlation between the peak-to-peak load applied and the measured amplitude of the thermoelastic signal as shown in Fig. 5a.



(b) (c)

Fig.5. (a) Thermoelastic signal measured versus stress amplitude; Correlation coefficient of the linear regression for all sampled points: (b) single frame; (c) 24 frames.

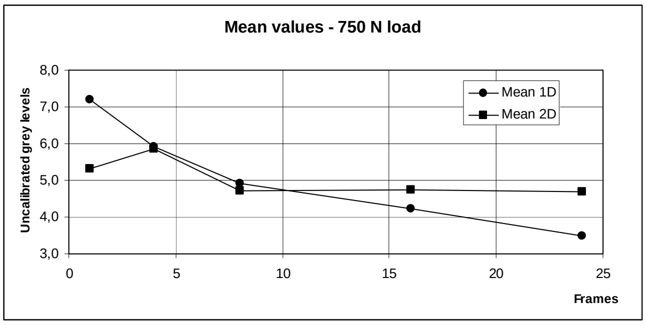
Since a linear relationship between the thermoelastic signal and the loading amplitude is predicted by the thermoelastic effect law (see eq. 1), the correlation coefficient of the linear regression can be used as a parameter to quantify the ability of the processed experimental data to follow the ideal linear behaviour, and hence the quality of results. Results in Fig. 5b) are referred to a single grabbed frame and in Fig. 5c) to an extended sampling window of 24 joined frames.

It is seen that performing the analysis on a higher number of joined frames dramatically improves the linear trend between the thermoelastic signal and stress amplitude. It must be noted that for the present case of a uniform stress field each scanned point should deliver the same thermoelastic signal.

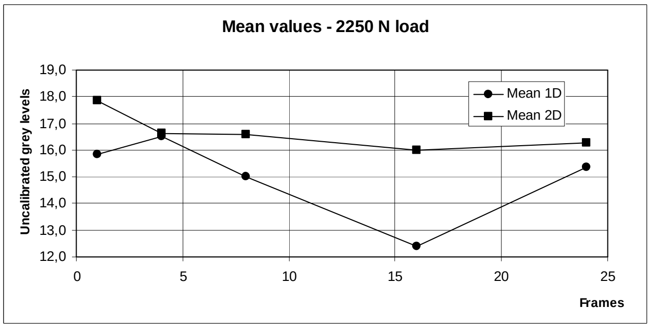
Experimental activity has moved further to investigate the benefits of implementing a 2D FFT based lock-in analysis of the acquired frames [4], coupled with the proposed data extension procedure.

The same experimental data frames recorded on polycarbonate tensile samples undergoing sinusoidal load at different traction-traction load amplitudes with peak-to-peak load ranging from 750 to 2250 N, have been initially processed to obtain extended data set joining up to 24 single data frames. Then each data set containing different number of single joined data frames (1 - 4 - 8 - 16 - 24) has been processed by 2D FFT lock-in analysis. This will enable to compare the effectiveness of 1D FFT based lock-in analysis to that of the 2D-FFT, and to check to what extent both the 1D and the 2D-FFT can benefit of the preliminary time domain data extension procedure.

Given that the nature of the noise affecting the thermoelastic signal (e.g. NETD of the thermocamera) is mainly stochastic, the analysis of the mean and standard deviation values of the thermoelastic signal can be useful to highlight the different performances of both the 1D and the 2D-FFT lock-in based filtering procedure applied to the investigated signal.



(a)



(b)

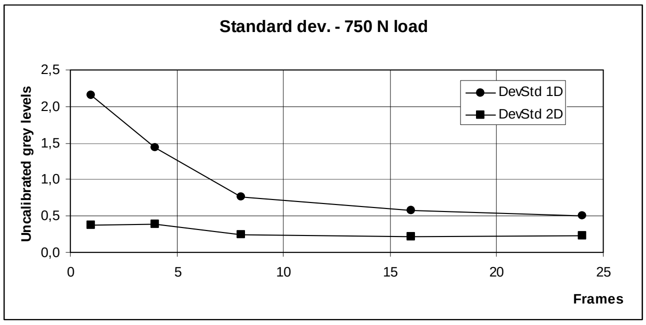
Fig.6. Mean values of thermoelastic signal filtered with the 1D-FFT and 2D FFT algorithms applied on extended frames versus the number of concatenated frames and for peak to peak load amplitude of a) 750 N; b) 2250 N.

In Fig. 6 the trend of the mean value obtained when the sample is subjected to minimum and maximum value of the peak-to-peak load, respectively 750 and 2250 N, are shown for different processed signal obtained at different number of joined frames.

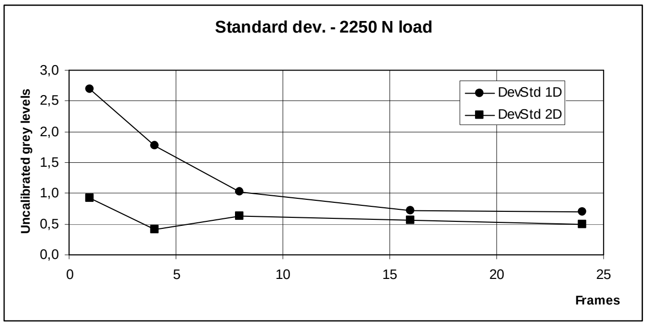
The comparison show that results obtained by 2D-FFT have a significantly smaller variation as the number of concatenated frames increases, and can be substantially considered stable when processing signals from eight or more concatenated frames; this performance is obtained both at the lower (fig. 6a) and at the higher (fig. 6b) peak-to-peak loading values.

On the contrary, the signals processed by 1D-FFT show mean values significantly dependent on the number of concatenated frames and presenting a high range of variation, without settling at a stable value even for the highest number of concatenated frames. It is also worth to observe that at the lower loading amplitude (750 N), the mean value of the thermoelastic signal processed by the 1D-FFT, is almost halved moving from a single frame to 24 frames, therefore showing the lower quality of the 1D-FFT processed data.

Analogous considerations can be formulated on the ground of results shown in Fig. 7, for the standard deviation data calculated on the same thermograms. Standard deviation values calculated on the thermograms filtered by the 2D FFT lock-in based algorithm are always lower than those obtained by the 1D-FFT.

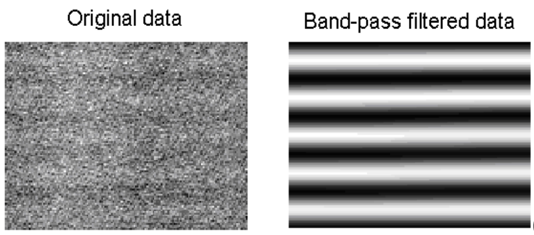


(a)

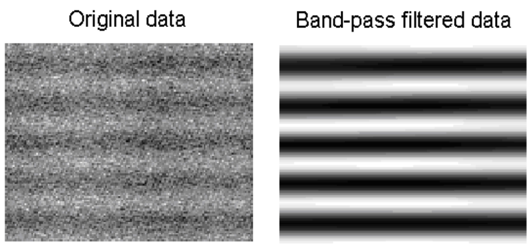


(b)

Fig.7. (a) Standard deviation of thermoelastic signal (load 750 N)
(b) Standard deviation of thermoelastic signal (load 2250 N)



(a)



(b)

Fig.8. Influence of the 2D-FFT band pass filter on the temperature maps at load amplitudes of (a) 750 N, (b) 2250 N.

Figure 8 shows the result of the application of a 2D-FFT band pass filter around the load carrier frequency on the temperature maps acquired at peak-to-peak load amplitudes of 750 N and 2250 N. It is interesting to notice the high quality already gained by the filtered maps in fig. 8, after the initial 2D-FFT band pass filter and before the mixing with the F and G signals and subsequent final low-pass filtering operation (see scheme in fig. 2).

The 1D and 2D FFT based filtering approaches are also compared in terms of their ability to recover the linear trend of the thermoelastic signal with the load amplitude. This comparison is shown in Fig. 9 where thermoelastic signal is plotted versus the peak-to-peak load amplitude. It is noted that the thermoelastic signal uncalibrated unit is the grey level amplitude as measured in the original thermogram (an eight bit greyscale image).

Given the loading condition of the investigated tensile samples, the grey level amplitude of the thermogram has in theory a linear relationship with the tensile load applied (as already pointed out in fig. 5).

Results obtained after processing by means of both the 1D and 2D FFT based filtering procedures are shown in Fig. 9(a) for a single frame data set and in Fig. 9(b) for a 24 frames data set. The data processed by the 1D FFT show a lack of quality at the lower level of the applied load (750 N) when the data set consists of a single frame, whose set of results differs appreciably from that obtained from the data set containing 24 frames. Data processed by the 2D FFT show instead an almost negligible difference between those obtained by processing a single data frame and those obtained by processing a 24 frames data set. In fact the comparison of their linear interpolations provides results very similar in both cases (1 and 24 frames) and with a higher coefficient of correlation compared to those of 1D-FFT.

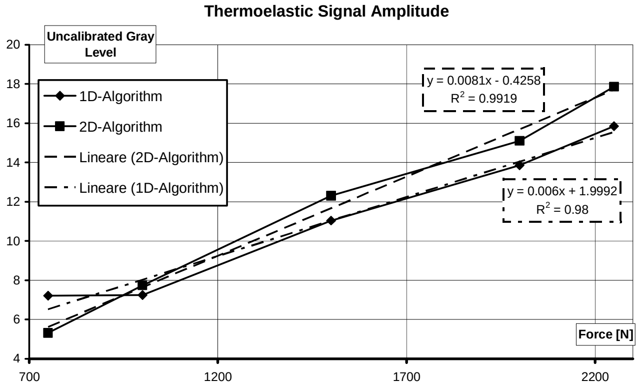
5. CONCLUSIONS

In the present paper a lock-in algorithm is presented to extract the thermoelastic signal from temperature data acquired versus time by means of a linear infrared scanner. The lock-in procedure implements 1D or 2D FFT based filtering algorithms and a procedure to obtain extended sampled data over time. The whole signal processing strategy has been tested on experimental temperature maps recorded on a tensile specimen undergoing tension-tension sinusoidal load. The time domain data extension procedure has been proposed to enhance quality of the data set, acquired using a low cost IR scanner with a 1 Hz frame rate and a 360×240 pixels single frame extension. Results obtained have evidenced the effectiveness of the proposed data extension procedure, which can be observed at a different extent when coupled to 1D or 2D FFT data filtering implemented in the lock-in scheme.

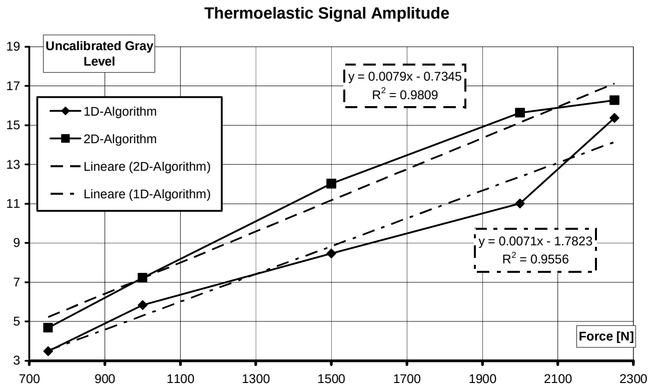
The 2D FFT has resulted in a more effective and robust filtering approach, fit to process the case of a uniform stress field.

The 1D FFT approach, though less effective in filtering, is at present more straightforward to apply in the analysis of more complex two-dimensional stress fields, since the signal from each acquired point is treated separately. However, in order for the 1D FFT approach to provide quality results it is essential to extend sampled data over the time domain.

The present work has demonstrated the potential of the presented methodology to process thermoelastic signals using low cost IR scanners. Further work is being devoted to the application of the methodology to the analysis of two dimensional stress distributions.



(a)



(b)

Fig.9. Measured Thermoelastic Signal versus stress amplitude: (a) single frame; (b) 24 frames.

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