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A novel tool for Non Destructive Testing using frequency analysis of IR image sequences

Abstract

In this paper, a novel methodology and a software tool for advanced image processing of thermal image sequences are presented. The software implements 1-D Fourier, short-time Fourier and wavelet transforms. The tool uses temperature variation in time for each pixel in the sequence of IR images. It is dedicated to Non Destructive Testing (NDT) testing and the functional time-dependent thermal imaging, e.g. for screening in medical diagnosis. The overall methodology is based on 2-stage analysis. The first, preliminary one is to estimate the right scale/frequency and the moment in time for the final frequency analysis. It can simplify characterization of materials and detection of cracks and defects.

Keywords: IR thermography, wavelet, Fourier, short-time Fourier transforms, functional thermal imaging.

1. Introduction

There are many methods of image processing used for Non Destructive Testing [1-5]. Among them, the Frequency Analysis (FA) is one which was the very first and it is still in use [1]. There are 3 main methods of frequency signal processing: Fourier Transform (FT), short-time Fourier Transform (STFT) and Wavelet Transform (WT). In thermography, FT and WT have been already used, but not as extensively as it could be [1, 3, 5]. There is no comprehensive software available for IR image processing based on FT, STFT and WT compatible with many thermal cameras available on the market today.

FA of IR thermal image sequences seems to be very effective approach because it suitable for different experimental scenarios. It is mainly dedicated to lock-in thermography, where the fundamental frequency component is dominant both for power excitation and temperature response. FA is also very useful both for transient and pulse thermography. It is because the curve of the temperature vs. time consists of many harmonics. One can choose the right one for its application.

In this paper we present a novel approach using 2-stage frequency analysis for advanced thermal image processing for NDT applications. Thermography in NDT is based on heating or cooling an object and measuring the temperature response in the dynamic state, while temperature is oscillating, raising or decaying in time. After recording the sequence of images, the post processing is performed to detect, recognize or/and characterize an object, different defects, etc.

2. Two-stage algorithm of IR image processing using wavelet, Fourier and short-time Fourier analyses

The method of thermal image processing presented in this paper consists of two main steps. In the first one called the preliminary analysis, the processing of temperature evolution in time for a point on the IR images is performed – Fig. 1. The user looking at the sequence of thermal images, selects a point and decides where to start the initial, preliminary analysis. Typically, one selects the most varying, the least noisy or the most contrast region for the preliminary transformation. It is possible to select a single point or a small region containing e.g.: 3×3 or 5×5 pixels.

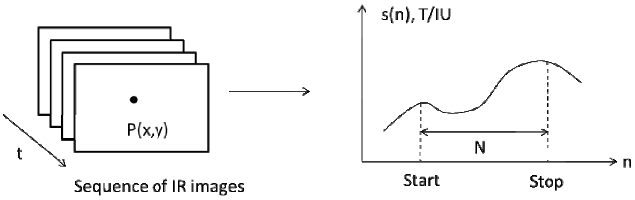
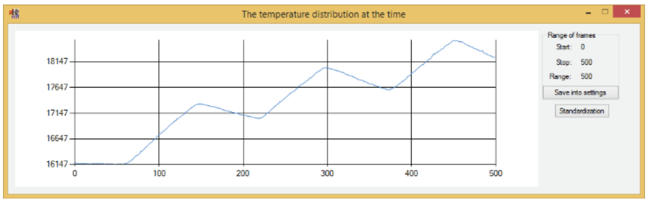


Fig. 1. Sequence of IR images and the selected point P(*x*, *y*) for the preliminary analysis

The exemplary result of the temperature evolution in time is presented in Fig. 2 for lock-in thermal measurement. One can see the transient thermal process after starting the heating with an oscillating heat source.



Range of frames
Start: 0
Stop: 500
Range: 500

Fig. 2. Temperature variation vs. time (frame no.) for lock-in experiment

In some experimental investigations a long-term temperature rise or decay is observed – Fig. 2. It is due to the transient thermal process being far away before the quasi-static state. A problem arises when one stops the recording earlier, before the quasi-static state, and introduces the large temperature change into the FA. It is because classical FA assumes the periodicity of the signal which is actually processed. In other words, there is a significant non-continuity in the temperature evolution. The result of it is that the non-existing frequency components appear in the spectrum, especially at high-frequency range. In order to reduce this effect we propose the widowing operation before the frequency transforms – Fig. 3. It an optional operation just before the preliminary frequency analysis.

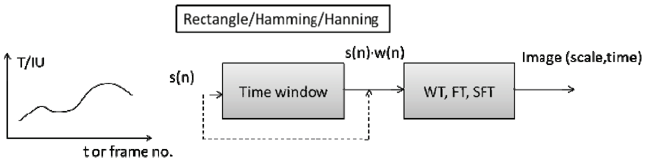


Fig. 3. Preliminary frequency analysis for a selected point on the thermal images

As the result of the preliminary wavelet analysis, one gets the 4 images: real, imaginary, modulus and angle ones – Fig. 4. The aim of the preliminary analysis is to select the appropriate scale/component frequency and the moment in time for final analysis for whole image and entire sequence. It can be done by finding the spectrum component corresponding to the temperature variation. Typically, the fundamental harmonics (in lock-in approach) is the largest one, and it is the best to choose it for further analysis. In the most of cases, it contains the sufficient information about the defect because of the low noise content. In Fig. 4 the appropriate scale is selected by simple comparison time dependent temperature (Fig. 2) and the spectrogram (Fig. 4).

Because of almost 3 periods were recorded in time, the scale with 3 periods at the spectrogram is chosen for the final analysis (Fig. 4).

A similar methodology of selecting the right spectrum component can be adapted to FT and STFT. For FT and STFT, the results are presented in Fig. 5. One can see the harmonics corresponding to the temperature oscillations in time. In case of temperature evolution from Fig. 2, the best choice was to select the 3rd component of the spectrum – Fig. 5. The same operation can be performed in STFT. Moreover, for STFT one has the another possibility to choose the appropriate position of the sequence in time. It allows to synchronize the thermal response with the power excitation to get more contrast on amplitude and phase images.

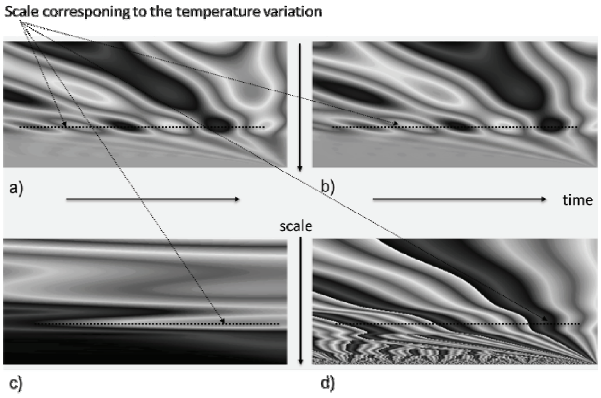


Fig. 4. Result of preliminary wavelet analysis for a selected point on the thermal images (temperature vs. time in Fig. 2) a) real, b) imaginary, c) modulus, d) angle images

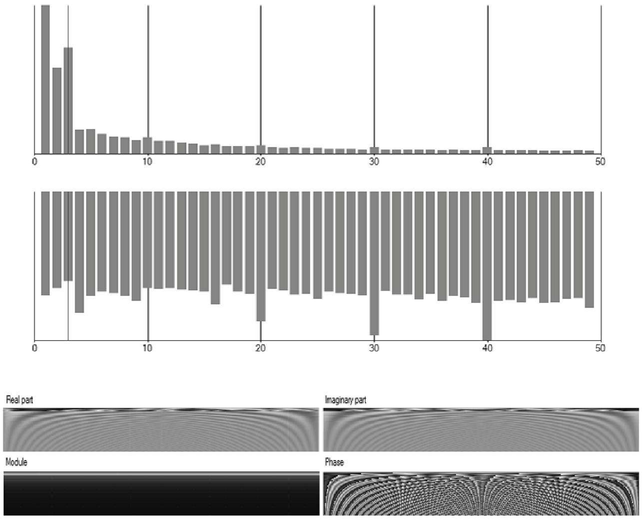


Fig. 5. Results of preliminary FT and STFT for the time dependent temperature curve in Fig. 2 for n=50th harmonic component

The preliminary analysis for STFT gives 4 images (real, imaginary, modulus and phase) – Fig. 5. The images in Fig. 5 are for n=50th harmonic component with the time scale on the horizontal axis 0-10 s and the time step 20 ms. It denotes that the frequency resolution of the spectrum is 0.1 Hz.

After preliminary analysis, the final one is performed to characterize the material and to localize a defect, non-homogeneity, or delamination in an object. The scale, position in time for WT and harmonic component number for (FT and STFT) from the preliminary analysis are now taken to the final one – Fig. 6.

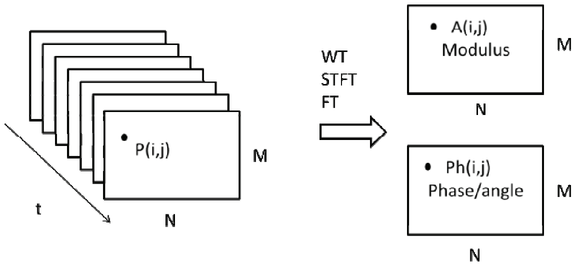
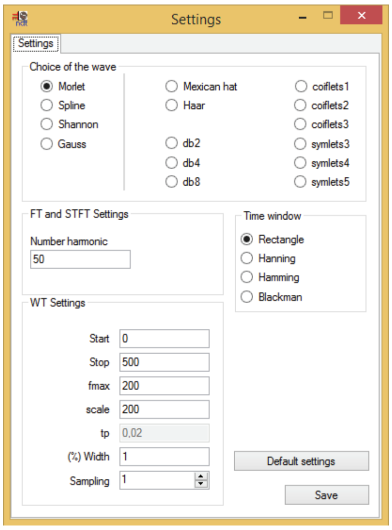


Fig. 6. Final analysis for a given scale, position (WT) in time and spectral component (FT, STFT)

In order to perform both analysis: preliminary and final ones, the set of parameters has to be settled – Fig. 7. WT can be performed for different real and complex wavelets: Morlet, B-spline, Shannon, Gauss, Mexican hat, Haar, Daubechies, Symlets and Coiflets. In addition, user can define the window type, the parameters of the wavelets, such as central (maximum) frequency, width and maximum scale value. One can cut off the beginning and the end of the sequence by defining the first and last image taken for the analysis. "Sampling" in settings (Fig. 7) means the gap in between the successive images (frames) taken for the analysis. E.g., if sampling is equal to 3, every 3rd frame is taken to the analysis. This parameter is very helpful for very large sequences to shorten the analysis and increase the performance of the overall processing.



Choice of the wave
● Morlet
○ Spline
○ Shannon
○ Gauss
○ Mexican hat
○ Haar
○ db2
○ db4
○ db8
○ coiflets1
○ coiflets2
○ coiflets3
○ symlets3
○ symlets4
○ symlets5

FT and STFT Settings
Number harmonic: 50

Time window
● Rectangle
○ Hanning
○ Hamming
○ Blackman

WT Settings
Start: 0
Stop: 500
fmax: 200
scale: 200
tp: 0,02
(%) Width: 1
Sampling: 1

Fig. 7. Frequency analysis's setting window

The initial width (the smallest one) of the wavelets is expressed in %. Its definition is as in Fig. 8, width = 100% $\cdot T_{50\%}/T_0$.

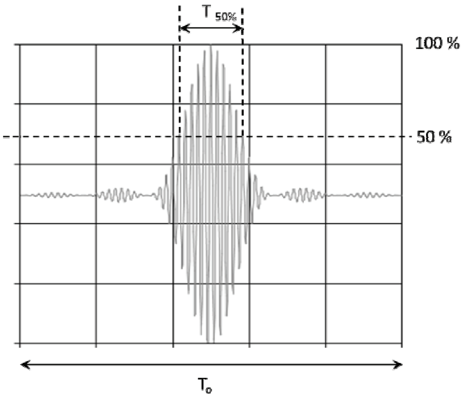


Fig. 8. Definition of the width of the wavelet for at the example of Morlet's wavelet

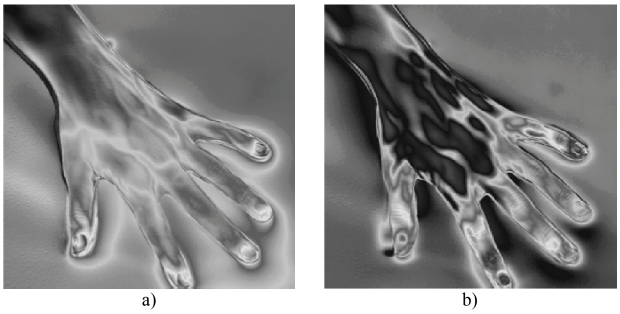
3. Exemplary results

In order to illustrate the possible applications of the presented tool for frequency analysis of thermal image sequences, a few examples are presented starting from medical ones and finally showing the inner, hidden object detection.

The first example presents the application of the presented tool for cold stress of a hand. It is the typical functional imaging used for screening purposes in medicine today. The hand of a patient was put into 20°C water for about 10 s. At first, the sequence of images was recorded, and then 2-stage analysis started. By choosing the right wavelet, the scale and position in time, it was possible to visualize the superficial vessels – Fig. 9. In such a case, the proposed method is applied like in the classical NDT using thermal imaging. One can say, that it is similar to the thermal tomography technique. Moreover, the depth of the vessel detected strongly depends on the frequency of the power excitation. For transient thermography, one can choose the right frequency of analysis because almost whole spectrum is available. As a result it is possible to estimate the size and the depth of the investigated object (in this case – the parameters of the vessel). Some experience is needed to choose the appropriate technique of cooling and adequate parameters of FA.

Fig. 9. Thermal tomography example using wavelet transform: complex Gauss wavelet, modulus, scale=176

In Fig. 10, one presents thermal reaction of the fingers after cooling down. The reaction is different for 2 fingers in comparison to the other ones. At the beginning all fingers are reacting similarly. The tips of the fingers are in red on the phase image for Morlet wavelet with the scale 114 – Fig. 10a. Little and index fingers react with a certain delay. These fingers are visible in red on phase image taken for lower frequency, scale = 66. This experiment confirms the usefulness of complex Morlet wavelet analysis and the phase imaging. The delay can be quantified by measuring the exact value of the phase in the appropriate ROI and by using the frequency (scale) of the analysis. The results presented in Fig. 9 and 10 were obtained using the cooled InSb thermal camera with NETD=17 mK and 50 Hz frame rate.



a) b)

Fig. 10. Delay in thermal reaction of the fingers after cold provocation, wavelet transform: complex Morlet wavelet, phase, a) scale 114, b) scale=66

The results of the next example of using FA for thermal image sequence are presented in Fig. 11 and 12. We were using the wavelet analysis to locate an hidden microelectronic chip and its antenna for powering the electronics in the RFID card. In this case, the classical lock-in thermography was applied. The excitation frequency was about 0.1 Hz. A flash lamp was used to heat up the sample. This lamp was placed on the other side of the object than the thermographic camera. The microbolometer uncooled camera was used in this experiment with *NETD* = 40 mK and low frame rate registration at about 10 Hz. The aim of this experiment was to detect and localize the chip and the antenna. Because of the small size of the chip, the higher frequency was selected for Gauss wavelet, scale = 144. One should notice, that the higher value of the scale corresponds to the higher the frequency of the analysis.

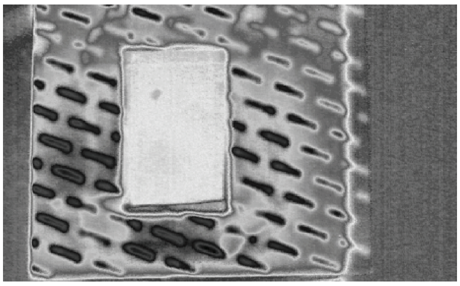


Fig. 11. Detection of the chip hidden in the RFID card, Gauss wavelet, phase image, scale = 144

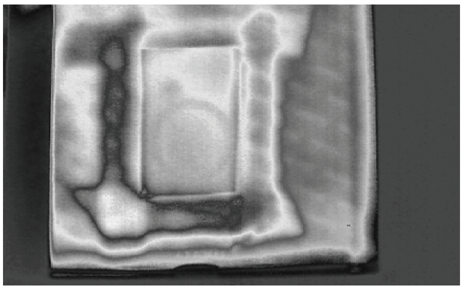


Fig. 12. Detection of the antenna hidden in the RFID card (ring in the image), Gauss wavelet, phase image, scale = 22

For lower frequency component (scale 22), the antenna becomes visible – a ring in Fig. 12.

All experiments in this research were performed using the new software that has been developed lately – *TEndt v.* 1.5 [6]. The first version of this software is mainly for NDT applications. It is dedicated to lock-in thermography directly, but as it was mentioned in the text it suits for pulse and transient thermography as well. The software incorporates with different thermal cameras available on the market. The only requirement is the have the software interface between the camera and computer. Typically such a link can be easily established using the drivers and SDKs delivered by the manufacturer of the camera. The software will be extended soon by implementing thermal impedance analysis and modelling, as well as thermal image feature extraction and selection for advanced classification.

4. Conclusions

Frequency analysis of the thermal image sequences is one of the possible approach for NDT using thermography. It has a greater potentiality now because of the progress in applications of wavelets in many different signal processing domains. One of them is thermography. The wavelets have the opportunity for self-adjustment into the temperature variation in time. The 2-step methodology of thermal image processing presented in this paper gives a simple way to select both the right scale/frequency and the position in time to get more effective defect detection and material characterization. Different wavelets give the another degree of freedom in selecting the appropriate tool for a given application.

STFT seems to be an effective tool for thermographic NDT as well. It is similar to WT with harmonic wavelets.

The software presented in this paper will evaluate towards the more advanced analysis, especially using the concept of thermal impedance, thermal time constants distribution and thermal modelling is the Laplace domain. Implementing thermal features of thermographic images and their sequences will be the next step in the research. Described methodology and software can be applied in many different areas – e.g. control and monitoring of some technological processes. It can be also applied in medicine for noninvasive, contactless screening.

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